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Status of the International Terrestrial Reference Frame: ITRF2014 and future developments

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We review the progress and continuous improvements being made since more than 30 years in the determination and development of the International Terrestrial Reference Frame (ITRF). We evaluate the precision and accuracy of the main geodetic and geophysical products of the latest ITRF release, namely the ITRF2014, using some key performance indicators. These indicators include the evaluation of the performance of the annual and semi-annual signals and Post-Seismic Deformation (PSD) models: the two main innovations introduced in the ITRF2014 elaboration. We address some scientific questions of space geodesy contribution, via ITRF2014 results, to understanding geophysical processes that affect the Earth system, such as earthquake displacement, tectonic motion, glacial isostatic adjustment, geocenter motion and loading effects. We evaluate in particular the performance of estimating periodic signals versus applying a non-tidal atmospheric loading model, as well as the extrapolation of the PSD models beyond the ITRF2014 time-span for sites that are subjects to major earthquakes. A particular emphasis will be devoted to the level of agreement between techniques in terms of frame physical parameters (origin and scale), Earth Orientation Parameters, and consistency with terrestrial local ties at co-location sites. Main conclusions will be drawn to guide and improve our analysis and combination strategy for future ITRF developments.

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Analysis of the seasonal parameters estimated in the ITRF2014 processing

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Annual and semi-annual periodic coordinate variations have been estimated simultaneously with positions and velocities of geodetic sites in the first step of the ITRF2014 processing. Four datasets are available corresponding to the four geodetic techniques, namely Global Navigation Satellite Systems, Very Long Baseline Interferometry, Satellite Laser Ranging and Doppler Orbitography and Radiopositioning Integrated by Satellites. At sites where stations of several techniques are operating, the seasonal parameters are worth comparing. Indeed, within a co-location site, nearby instruments are supposed to measure the same physical ground motion. As a consequence, any discrepancy between techniques could be interpreted as technique-specific errors if annual and semi-annual ground motions are computed over the same period. Thus, the aim of this paper is to evaluate the level of agreement of seasonal parameters estimated by different techniques at co-location sites.

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JTRF2014: A Time Series Representation of the ITRF

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The Jet Propulsion Laboratory (JPL) is pursuing an approach to determining ITRF-like terrestrial reference frames based upon the use of a Kalman filter/smoother. Kalman filters are commonly used to estimate the parameters of some system when a stochastic model of the system is available and when the data contain noise. For the purpose of determining a terrestrial reference frame, the system consists of the positions and velocities of geodetic observing stations and associated EOPs along with their full covariance matrices. The data consist of time series of observed VLBI, SLR, GNSS, and DORIS station positions and EOPs along with the data measurement covariance matrices. In addition, measurements from ground surveys of the positions of reference marks of co-located stations are used as constraints to tie the technique-specific measurements to each other. JPL's Kalman filter and smoother for reference frame determination (KALREF) combines these measurements to determine ITRF-like reference frames subject to constraints imposed on the allowed evolution of the station positions. KALREF includes options to model the station motion as linear, linear and annual, or linear, annual, and semiannual. Through the use of stochastic models for the process noise, the station positions can be constrained to follow these models of the station motion (by setting the process noise to zero), to recover the observed station positions (by setting the process noise to a large value), or to follow a smoothed path (by setting the process noise to some intermediate value). The time series approach to determining terrestrial reference frames that is being pursued at JPL will be described along with its use to determine JTRF2014, JPL's realization of a terrestrial reference frame using the ITRF2014 input data sets.

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DGFI-TUM analysis and scale investigations of the latest terrestrial reference frame realizations

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Solutions for the most recent realizations of the International Terrestrial Reference System (ITRS) were computed by the three ITRS Combination Centers (CCs) of the International Earth Rotation and Reference System Service (IERS), namely the IGN in Paris (France), the JPL in Pasadena (US) and the DGFI-TUM in Munich (Germany). Thereby, the solutions of IGN and DGFI-TUM comprise conventional parameters of the ITRS (station coordinates and velocities) at a reference epoch as defined in the IERS Conventions 2010 (Petit et al., 2010). The two solutions are based on identical input data, but differences in the ITRS realization strategies lead to systematic differences between them.
The most important differences are the combination of normal equations systems versus the combination of solutions, the application of non-tidal loading models versus the estimjation of annual and semi-amnnual signals and the different handling of local ties.
Within all ITRS realizations, the scale is realized as a weighted mean scale between SLR (satellite laser ranging) and VLBI (very long baseline interferometry). If the combined scale is compared to the scale realized by both techniques itself, the IGN solutions shows significant differences between SLR and VLBI whereas the DGFI-TUM solution shows a better agreement.
In order to investigate the question whether there is a systematic scale difference between the two solutions or not, the combined solutions of IGN and DGFI-TUM as well as the single-technique solutions of both institutions are analyzed and compared. In addition, the impact of the used local ties on the scale realization is investigated. Moreover, the realization of the origin and the orientation of the two ITRS realizations is compared.

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IGS14/igs14.atx: Implications for IGS products

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On January 29, 2017, the International GNSS Service (IGS) adopted a new reference frame (IGS14), based on the latest release of the International Terrestrial Reference Frame (ITRF2014), as the basis for its products. An updated set of satellite and ground antenna calibrations (igs14.atx) became effective at the same time. IGS14 and igs14.atx replace the previous IGS08/igs08.atx framework in use since April 17, 2011 and in the second IGS reprocessing campaign (repro2).

The update from IGS08/igs08.atx to IGS14/igs14.atx covers three different aspects, each with different expected impacts on the IGS products. First, the update of the reference frame itself is expected to improve the precision of the alignment of the IGS products to the ITRF, since IGS14 includes more available reference frame stations with more precise and up-to-date coordinates than IGS08.

Secondly, compared to igs08.atx, igs14.atx includes robot calibrations for 17 additional ground antenna types and 19 updated type-mean robot calibrations. These calibration updates are expected to increase coordinate accuracy for stations equipped with these antennas and may also lead to improved repeatabilities of their position time series.

Finally, the radial components of all GPS and GLONASS satellite phase center offsets (z-PCOs) were updated from igs08.atx to igs14.atx. The satellite z-PCOs were changed by about -6 cm on average, changing the scale of the IGS daily solutions by about +0.5 ppb and bringing it closer to the ITRF scale. The update of the z-PCOs of recently launched satellites, from preliminary block-specific values to satellite-specific estimates, is additionally expected to reduce large-scale systematic errors in IGS station positions and in particular to stabilize the scale of the IGS daily solutions.

This presentation will first review the elaboration of IGS14 and igs14.atx. The different impacts of the switch on IGS products will then be quantified and discussed.

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The status of DORIS in light of ITRF2014

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The Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) is one of the four techniques of Space Geodesy that contributes to the International Terrestrial Reference Frame. It consists of a network of 55-60 beacons distributed nearly homogeneously around the Earth's surface, as well as a satellite segment including up to six receiving satellites in Low Earth Orbit. Recently the DORIS community reprocessed more than 22 years of data in order to develop the DORIS technique contribution to the ITRF2014 realization of the International Terrestrial Reference Frame (ITRF). Six analysis centers implemented a series of improvements in both measurement and force modeling in order to develop their contributions. The IDS Combination Center prepared the technique contribution which revealed that recent data since the launch of Jason-2 have an intrinsic positioning uncertainty 9, 7, 8 mm respectively in the North, East and Up components, and yield a standard deviation in the polar motion differences with IERS C04 of 245 (Px) and 235 (Py) microseconds.

We discuss in this paper the continuing improvements in the DORIS technique since the completion of ITRF2014. These include the efforts to process a rawer form of the DORIS observable in the RINEX format, the development of a routine combination of DORIS coordinates for application to precise orbit determination DPOD2014, and a preliminary assessment of the contributions of Sentinel-3A and Jason-3 to the DORIS weekly solutions. We also review the performance of the “C" generation of Starec beacons, whose phase centers are defined to +/- 1 mm, and whose development and deployment was initiated in light of the work done by the IDS for ITRF2014.

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Progress towards the third realisation of the International Celestial Reference Frame

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The presentation will review the progress towards the generation of the third realization of the International Celestial Reference Frame. The work for ICRF3 is carried out by a Working Group of the IAU with the aim of completing ICRF3 by 2018 for adoption at the IAU General Assembly in Vienna. ICRF3 will be based on state-of-the-art astronomical and geophysical modeling and will benefit from the wealth of VLBI data acquired since ICRF2 was built in 2009 (an additional 60% of data). Areas of work include selecting the datasets, defining the analysis configuration, identifying the stable sources, identifying the ICRF2 to ICRF3 transfer sources, and selecting defining sources for ICRF3. The latter takes advantage of the many VLBI images available to derive source structure indices which provide a mean to assess the astrometric quality of the sources. Specific attention will be paid to the treatment of Galactic aberration which affects VLBI data at a significant level due to the > 30 yr time-baseline. Besides the standard S/X band observations (2.3/8.4 GHz), data at K band (24 GHz) and X/Ka band (8.4/32 GHz) are being considered, while the recent Gaia Data Release (DR1) provides a unique check against optical positions. Finally, an additional stage which combines rigorously individual solutions into a consolidated VLBI catalog is also investigated.

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Testing of special relativity with geodetic VLBI

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The geodetic Very Long Baseline Interferometry (VLBI) measures the group delay observable in the barycentric reference frame. As the Earth is orbiting around the Solar System Barycentre with the velocity V of 30 km/s,the VLBI turns to be a handy tool to detect the subtle effects of the special relativity theory with a magnitude of (V/c)^2. The theoretical correction for the second order terms reaches up to 300 ps, and it is implemented in the geodetic VLBI group delay model. The total contribution of the second order terms splits to two effects - the contraction of the Earth scale in the plane perpendicular to the orbital velocity vector direction, and the displacement of the radio source apparent position. We are using the Robertson-Mansouri-Sexl (RMS) formalism to probe the Lorentz invariance. We analyse the geodetic VLBI data with two independent software packages (OCCAM and VieVS) and show that the parameters of the RMS model can be estimated with a high accuracy.

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Correlated atmosphere noise in VLBI analysis

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The standard assumption in the routine VLBI analysis is that the observations are station and time independent which manifests itself in a diagonal observation covariance matrix. But this simplification causes a mis-characterisation of the measured group delays leading to incorrect estimation of parameters and too optimistic formal errors. In the first step we compare the estimated baseline length scatter from CONTinuous VLBI campaigns using two ways of reweighting obsevations, i.e. adding baseline dependent and elevation dependent noise. In the second step we introduce correlations into the observation covariance matrix focusing on mis-modeling of the atmosphere and taking into acount correlations between observations at a common time. We demonstate that this reduces the baseline length scatter, indicating that the results are more consistent day-to-day. We also show that introducing the correlations improves the agreement between VLBI and GPS measured polar motion.

Ray-traced delays and global reference frames with geodetic VLBI

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Geodetic Very Long Baseline Interferometry (VLBI) observations have been carried out since 1979 with a total number of more than 10 million group delays as of 2017. We use operational and re-analysis data of the European Centre for Medium-range Weather Forecasts (ECMWF) with a temporal resolution of six hours and a spatial resolution of one degree to determine ray-traced delays for every single VLBI observation as well as to determine horizontal tropospheric north and east gradients for all sites every six hours. We then use those tropospheric delays in the analysis of all VLBI observations to estimate terrestrial and celestial reference frames and to compare the results against those from standard analysis setups. In particular, we assess the influence of refined tropospheric models on the declination of source coordinates, on station heights, and on baseline length repeatabilities.

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Space tie satellites for millimetre geodesy – a VLBI perspective

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Space tie satellites are of major interest in the geodetic community, bearing the potential of a major step forward in realising the terrestrial reference frame (TRF). Combining all four space geodetic techniques on a single satellite platform, this novel concept will improve the accuracy and stability of the TRF, in particular concerning the Geocentre, the scale and the connection to the inertial celestial frame. With sophisticated satellite missions being proposed and prototype missions already in space, thorough research is clearly trailing behind and highly necessary. This concerns predominantly the very long baseline interferometry (VLBI) part, since VLBI observations of low Earth orbiting satellites are absolutely novel.
In this contribution we report on a series of test observations which were performed using radio telescopes in Australia. Following essential developments in the observing setup and process chain, our main result is a six-hour time series of VLBI satellite observations using a set of GNSS satellites. Further we report on observations of the Chinese APOD satellite, which is equipped with a dedicated VLBI transmitter, using the Australian AuScope VLBI array. Having developed a complete process chain from the observations to initial geodetic results, we report on issues we have encountered and problems that still need to be solved. Hereby the focus is on optimal compatibility of existing VLBI station hardware and future space tie missions.
The first time series of VLBI satellite observations represents a breakthrough in this novel technique, now enabling further developments and bringing the first realisation of VLBI space ties within reach.

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Robust realization of a no-net rotation reference frame on a deforming tectonic plate

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We present a robust method of fixing a reference frame to a moving and deforming plate, using the example of North America. Scientific applications motivate that we fix the frame with a scale consistent with the SI system, an origin that coincides with the Earth system's center of mass, and with axes attached to the rotating interior of the plate. To realize this no-net rotation condition, a typical approach is to select a subset of "core stations" that have small residual velocities. Stations in the far field of plate boundaries and glacial isostatic adjustment can be selected to satisfy these criteria. However, such regions of the Earth's crust may appear to be rigid (e.g., ~0.3 mm/yr residuals for core stations in our NA12 frame), but the entire region can move relative to plate motion. Such common-mode motion biases plate rotation estimation, with implications on scientific interpretation. Our scheme presented here (1) starts with robust estimation of station velocities using our MIDAS algorithm, (2) then uses median spatial filtering to remove outlier stations that do not reflect the regional trend, and (3) performs simultaneous estimation of strain-rate tensor and rotation components for any chosen point within the plate using our new algorithm, MELD ("median estimate of local deformation"). MELD uses velocities from all possible triangles of stations enclosing each point within 2 or 3 nearest neighbors of the Delaunay Triangulation. From the parameter estimates of all local triangles, the median value for each strain rate and rotation component is then taken. From this analysis, we then take an area-weighted sum of rotations over all points to estimate plate rotation, which is then subtracted to define a no-net rotation, plate-fixed reference frame. This procedure estimates the rotation pole robustly, and the residual velocities prove to be significantly different than in frames realized using subsets of stations that appear to be internally rigid.

Three Dimensional Strain-Rate Field from Geodetic Measurements on the Surface

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Geodetic measurements for strain determination are in many cases carried out at the Earth's surface, thus topologically remaining in a 2D manifold. Even though changes in the third component are determined e.g. by levelling it will hardly be possible to determine the real 3D strain. Our method circumvents this problem by introducing a crustal model. Even simple models help and deliver quite realistic results as shown in this paper. In the case of Switzerland, however, this remains very demanding because of the very small yearly movements generating equivalently small yearly crustal distortions at a maximum of 25 nstrain per year. The available time series of GNSS and levelling measurements acquired and treated by the Swiss office of topography, are sufficiently long to reveal deformations in Switzerland. They make it possible to determine a coherent kinematic deformation field of Switzerland by geodetic means.
Further development of the ⊠Adaptive Least-Square Collocation (ALSC) ‘, which was devised at ETH, and the implementation of a physical crustal model made it possible to directly calculate a three dimensional strain tensor field out of the available measurements e.g. GPS and levelling. The geodetically determined strain-tensors are verified versus focal mechanisms obtained from seismological data. The mechanism of a recently induced earthquake mechanism in the region of St. Gallen close to a geothermal test site is in agreement with the strain tensors determined by GPS-data. The described method can also be applied to more local events, e.g. the analysis of subsidence or landslides. It will allow to gain more insight into subsurface processes from geodetic measurements.
The paper presents the method and shows results of geodetic determination of strain field in the complex tectonic setting of the Swiss Alps.
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Spatially correlated ground deformation models in reference frame estimation

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A terrestrial reference frame (TRF) is estimated from space-geodetic station-position data sets that are several decades long. The primary model upon which the data are combined has been the linear motion due mostly to plate tectonics and post-glacial rebound. In recent TRF realizations such as ITRF2014 and JTRF2014, models of local motions are introduced to improve the estimation accuracy. These additional models include post-seismic displacements as well as annual, semi-annual, and random ground deformations due to atmospheric loading and ground water storage loading. Although such motions are often regionally correlated, the models of these ground deformations are formulated to be strictly local in space at present. In this presentation, we present our approach to include spatial correlation in the context of the stochastic motion model of geodetic station positions used in the JTRF2014 realization. In particular, we focus on the use of time-varying gravity data from the GRACE mission to globally determine spatial correlations in seasonal ground deformation. We will incorporate the data-driven correlations in the stochastic model and then examine effects of the spatial correlations on the TRF estimates. We note that the GRACE data do not directly enter in the TRF (station position) estimates; instead, the spatial correlations estimated from GRACE data will be used as parameters of the stochastic model used in TRF estimation.

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Differential station coordinates changes (velocities) versus coordinate differences (epoch solutions) for realising the time dependence in ITRF

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The International Terrestrial Reference Frame (ITRF) and its continental densifications (e.g. EUREF, SIRGAS) provide differential coordinate changes (linear coordinate derivatives, i.e. constant velocities) for interpolating or extrapolating the reference station coordinates to an arbitrary epoch, e.g. for satellite tracking or precise terrestrial positioning. These station velocities are also applied for geographical interpolation of the movements of intermediate points, e.g. used in engineering, surveying, precise navigation, and geodynamic studies. If the velocities are not constant, e.g. due to effects caused by seismic events or environmental non-linear surface deformations, the interpolation or extrapolation between epochs has to be done piecewise for all contemplable periods and effects, and the geographical interpolation has to follow the same procedure which may be very complicated in unstable regions. The present paper describes an option to use frequent (e.g. monthly) epoch reference coordinates instead of velocities, and to use them for practical applications (e.g. geographical interpolation of time-dependent coordinates of other points of the Earth surface). The advantage is that the reference stations' epoch coordinates include all occurred changes between the epochs, i.e. linear and non-linear station movements, and discontinuities caused by seismic events or changes of the reference frame. The method is tested in global, continental and national networks and yields good results.

Kalman filter terrestrial reference frame solutions based on time-variable process noise

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In recent years, Kalman filtering has emerged as a suitable technique to determine terrestrial reference frames (TRFs), a prime example being the JTRF2014 solution by the IERS ITRS Combination Center at JPL. The time series approach allows variations of stations coordinates that are neither reduced by observational corrections nor considered in the functional model to be taken into account. These variations are primarily due to non-tidal geophysical loading effects that are not included in the IERS conventions (i.e., non-tidal atmospheric pressure, ocean, and continental water storage loading). It is standard practice that the process noise models applied in Kalman filter TRF solutions are derived from time series of the aforementioned geophysical loading effects and account for station dependent differences. So far, it has been assumed that the parameters of these process noise models are constant over time. However, due to the presence of seasonal variations and episodic events such as ENSO, this assumption does not truly reflect reality. In this study, we derive a station coordinate process noise model allowing for such temporal variations. Time series of daily non-tidal loading deformations between 1985 and the end of 2015 provided by GFZ Potsdam are used to calculate monthly process noise parameters for every single station. As a test case, this process noise model is applied in the computation of a TRF based on very long baseline interferometry (VLBI) data from over 4000 VLBI sessions during the same time frame. The resulting VLBI TRF is compared to a solution based on a constant process noise model, but otherwise on identical input data and Kalman filter setup. In particular, it is investigated which VLBI stations profit the most from a spatiotemporal process noise model and how frame defining parameters, such as the scale, are affected.

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Variant and Invariant Properties of Coordinate Transformation

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An invariant coordinate transformation is a transformation where the quadratic form of the weighted residuals is preserved regardless of the coordinate system in which the transformation parameters are calculated. This implies that the quality of the transformation is invariant with respect to the coordinate system.
An invariant coordinate transformation allows converting the transformation parameters that were calculated in one coordinate system to another coordinate system correctly, without the need to calculate the parameters again in the new coordinate system. It allows for a proper transformation of the same point in different coordinate systems.
This paper discusses the invariance property of coordinate transformation and shows the complexity of geodetic coordinate transformations, where some are invariant and others are variant. In variant transformations, the transformation parameters and the quality of the transformation depend on the coordinate system and its definition, an important situation to be aware of.
We discovered that the most common transformation in geodesy, surveying and related professions, the 7 parameters transformation, is invariant. However, with the widespread use of GNSS measurements, transformations with more than 7 parameters become more common and some of them are variant. The most general affine transformation with 12 parameters is invariant, but all transformations with a number of parameters greater than 7 and less than 12 are variant. Thus, the transformation is variant with respect to the coordinate system.

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E-GRASP/Eratosthenes: a satellite mission for improving the Terrestrial Reference Frame

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The accuracy and stability of a Terrestrial Reference Frame (TRF) that are required to detect the smallest variations (e.g. sea level rise) in the Earth system components have been identified by GGOS and the scientific community to be 1 mm for positions and 0.1 mm/yr for velocities. These GGOS requirements are far from being met today, mainly due to deficiencies in the realization of the TRF originating from (1) the difficulty to accurately measure the local ties between the reference points (intersection of axes of large instruments, phase centers of antennas) and (2) the fact that each space geodetic technique suffers from its own systematic effects.
In order to fundamentally improve this situation, the E-GRASP/Eratosthenes satellite mission has been proposed to ESA as response to the 2017 Earth Explorer-9 (EE9) call. E-GRASP will provide a highly accurate co-location of all four space geodetic techniques (GNSS and DORIS receivers, laser retro-reflectors, and a VLBI transmitter) in space, on the same satellite platform, with particular attention paid to the time and space metrology on board. Orbiting the Earth in a highly eccentric orbit for visibility reasons, E-GRASP will be fully complementary to co-location on the ground and will connect all the ground stations with its co-located instruments.
Many different simulations have been performed already, both, for selecting the best orbital scenario according to many geometrical, technical and physical criteria and for assessing the impact on the TRF, which is crucial to achieve the GGOS requirements.
The presentation will focus on the mission science, the instrumentation and scenario as well as the simulation results available today.

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Lunar Laser Ranging as tie between terrestrial and space reference systems

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Lunar Laser Ranging (LLR) data has been used since 1969 to determine various physical parameters of the Earth-Moon system. LLR also acts as the connecting technique between the reference systems fixed on Earth, Moon and in space. The estimated reflector coordinates in combination with the lunar ephemeris represent the selenocentric reference frame and its orientation with respect to the barycentric reference frame. LLR can contribute to the terrestrial reference frame, e.g., with the estimation of station coordinates and velocities and long-periodic nutation coefficients with periods between 0.5 and 18.6 years. The estimated accuracy of the nutation coefficients is about 0.1 milliarcsecond. The estimated accuracy of the coordinates and velocities of the stations on Earth is in the order of 1 cm and 1 mm/yr which is up to now one order of magnitude larger than the GGOS goals for the terrestrial reference frame. The deployment of new single-corner-cube reflectors on the Moon and the recent success in infrared ranging to the Moon at the French station in Grasse can help to get more accurate LLR data per year. Based on the LLR dataset up to the end of 2016 we show the recent results for the estimated reflector and station coordinates, station velocities and nutation coefficients. With simulated future data we illustrate possible improvements for these parameters within the next years up to 2030.

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Double-Differences Over Time for Space Geodesy Techniques with GNSS Satellites and Lunar Laser Reflectors

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We have already demonstrated that the main advantage of common-view double-differencing of SLR measurements to GNSS is in the reduction of systematic effects, leading to differential SLR with sub-mm or mm-accuracy. Here we extend the common-view SLR approach and make double-differences over time by considering the different observation times for all SLR measurements between all SLR stations. SLR range biases and small biases between SLR sessions are removed. The scale of the reference frame is preserved after double-differencing, potentially providing access to the utmost accuracy of SLR in the global GNSS solutions. This SLR approach allows accurate estimation of local ties between SLR and GNSS, since relative coordinates between stations can be estimated independently by GNSS and SLR, thus requiring only one local tie to be estimated between ILRS and IGS ground networks. We have already demonstrated that the double-difference SLR approach with GNSS orbits from IGS offers a bias-free estimation of relative coordinates between ILRS stations with mm-accuracy separated by up to some 5000 km.

The same approach could also be applied between Lunar laser ranging (LLR) and SLR to GNSS satellites. We form double-difference LLR between two Lunar retroreflectors and two LLR stations to show the noise of the LLR of about 5-7 mm standard deviation. We managed to process LLR as one-way measurements in a geocentric frame similar to the processing of SLR to GNSS satellites and make use of the latest Lunar DE430 ephemerides and libration models. We present the estimation of the Lunar orbit and EOPs (including UT1 or UT0). This offers an interesting application of SLR and LLR in the global GNSS solutions, giving, in addition to scale, a potential access to UT1 or UT0 in the global GNSS solutions.

In the last part, we discuss a possible use of double-differences over time for the estimation of GNSS biases and resolution of integer ambiguities, as well as a possible extension to VLBI.

*G01-4-04
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Multi-Year Analysis of GNSS Local Ties at Fundamental Sites

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With increasing requirements on accuracy and stability for the realisation of the International Terrestrial Reference System (ITRS), the comprehensive analysis of technique-specific systematic biases in local measurements becomes crucial for the improvement of ties among space geodetic techniques. The quality of the ITRS realisation, the International Terrestrial Reference Frame (ITRF), relies on the adequacy of the ties of individual space geodetic techniques at fundamental sites. To this end, intra-technique co-location, where two or more co-located instruments of the same technique are available, constitutes an essential step for analysing individual biases on short baselines. Although Global Navigation Satellite Systems (GNSS) are one of the major contributors to the realisation of the ITRF, discontinuities in time series associated with hardware and software changes pose a major threat for their proper utilisation. Co-located GNSS at fundamental sites provide the opportunity of improving the accuracy of estimated positions by examining data breaks, local biases, deformations, time-dependent variations and the comparison of GNSS baselines with existing local tie measurements. Typically equipped with an array of several GNSS receivers collecting data continuously for several years, their proximity grants similar tropospheric delays, identical ionospheric conditions, same loading effects and nearly identical station motion.

With the use of precise GNSS orbits, an ambiguity fixing strategy and an appropriate parameterisation, this contribution presents a global multi-year analysis of a subset of IGS fundamental sites for delivering homogeneous coordinate time series and phase residuals, based on L1, L2 and the ionosphere-free linear combination with and without troposphere estimation, to quantify hardware and software changes, antenna patterns, environmental effects, local deformations and other time-dependent variations of the local baselines.

*G01-4-05
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Non-linear Geocenter Motion from Multi-Technique Geocentric Station Coordinate Time Series in a Terrestrial Reference Frame on Dynamic Earth and GRACE Gravity Data

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Spherical harmonic expansions of Earth's surface mass variations start from three degree-1 terms. These induce geocenter motion between the center-of-mass of the total Earth system (CM) and the center-of-figure of the solid Earth surface (CF), as well as a degree-1 surface deformation field. However, GRACE's K-band ranging data system is not sensitive to these variation modes. For complete spectral coverage and robust assessment of geographic mass budget using GRACE data, very accurate knowledge of geocenter motion is required but difficult to obtain.

To address the ever-changing nature of the solid Earth surface, recently, an experimental Kalman filter and time series terrestrial reference frame (KALREF) has been realized by a collaborative effort of JPL and IGN to determine nearly instantaneous geocentric station coordinates of all 4 space geodetic techniques. Through local tie measurements and co-motion constraints, satellite laser ranging (SLR)'s CM sensitivity is transferred to other technique networks, and SLR's many data gaps are bridged by co-located dense GPS data. For geocenter motion determination, we use a new unified approach by combining KALREF geocentric displacements of a larger and better-distributed 82-site network with GRACE gravity data. Both translational and deformational signatures will be exploited for retrieval of the degree-1 surface mass variation coefficients. Higher degree terms are estimated simultaneously using GRACE gravity data, which further improves CF knowledge and reduces aliasing effects. Such a data combination also uses full covariance matrices of all data types to facilitate a reliable variance component estimation. The combination of the 82-station KALREF coordinate time series with GRACE improved the precisions of non-linear geocenter motion components by factors of 2 to 3 compared with those obtained from the combination of SLR and GRACE.

*G01-5-01
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The Geocentric Datum of Australia 2020

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In 2017 the Australian federal, state and territory governments implemented a new datum for the spatial community. Named the Geocentric Datum of Australia 2020 (GDA2020), the datum will supersede the existing datum, the Geocentric Datum of Australia 1994 (GDA94). GDA2020 is a densification of International Terrestrial Reference Frame (ITRF) 2014 in Australia and is based on over 20 years of continuous GPS observations together with almost 2 million terrestrial geodetic and campaign style GPS observations. Implementation of GDA2020 is the initial phase of a longer-term government program to transition Australia to an ITRF based georeferencing system and to encourage the widespread application of time-varying coordinates. This presentation will overview the technical aspects of implementation of Australia's new datum including the development of an Australian plate model, the approach adopted for the national geodetic adjustment and the GNSS analysis strategy.

*G01-5-02
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Continuing and Emerging Roles of National GNSS CORS as Geodetic Infrastructure: Case study of GEONET in Japan

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GEONET, the national GNSS Continuously Operating Reference Stations (CORS) network of Japan, has been operational since 1996, celebrating the 20th year anniversary. Here we review the past 20 year operation of GEONET, and discuss continuing and emerging roles as Geodetic infrastructure.

Currently GEONET consists of 1,318 stations covering whole Japan with about 20 km spacing, tracking signals from GPS, QZSS, GLONASS and Galileo with 1 Hz sampling. Observation data and products are open to the public to support surveying and mapping. Private companies provide network-based realtime kinematic positioning services using data from GEONET, now widely used for ICT constructions and precision farming. Crustal deformations are monitored by time series of baseline vectors, revealing secular, coseismic, and postseismic deformations as well as slow slip events. The realtime analysis system for rapid deformation monitoring (REGARD) is now in operation, aiming to assist Tsunami warning. Thus GEONET has become the social infrastructure for surveying, mapping, positioning, disaster mitigation and Earth science.

Because of large and complex nature of crustal deformation around Japan, maintenance of the national reference frame needs extreme cares. So far, GEONET identified nearly 100 crustal deformations associated with large earthquakes. The 2011 Tohoku earthquake (M 9.0) is the largest one, recording 5.3 meter horizontal displacement, and still causing post seismic deformation. We need GEONET to generate semi-dynamic correction parameters that account for accumulated crustal deformations after the revision of the Japanese Geodetic Datum in 2011.

Although relative positioning that forms a baseline to delete common positioning errors is the old and reliable method for GNSS surveys, Precise Point Positioning (PPP) and PPP-AR (Ambiguity Resolution) that do not form baselines are emerging. We show the new role of national CORS is to provide sufficient local data for quicker fix of PPP.

*G01-5-03
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Japan-1sec1cm accuracy -Geodetic Network Adjustment

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Having learned from Kobe Earthquake (1995) and East Japan Earthquake (2011), future solutions are proposed on satellite surveying, satellite image photogrammetry. Parameter Estimation Gnss Assisted SUrveying System (PEGASUS for short) realizes 1 sec 1 cm accuracy geodetic network adjustment for earthquake monitoring. Now in Japan Basic Act for National Resilience Contributing to Preventing and Mitigating Disasters for Developing Resilience in the Lives of the Citizenry (Act No. 95 of December 11, 2013) has started, and for application of land administration systems, like Cadastre2014, Land Administration Domain Model Standard and Social Tenure Domain Model, we prepare for reconstruction plans, using 4D Image Map Archive Designed Aerial Survey (IMADAS for short) technology and German AAA Land Information System.
Kumamoto and Tottori earthquakes in Japan in 2016 motivated nationwide geodetic network adjustments, 1 sec 1 cm accuracy approach, for earthquake monitoring in 3D displacement in the world geodetic datum. We tested feasibility of such 1 second GNSS geodetic network adjustment to forecast the earthquake deformation of monitoring points. For reconstruction process after earthquakes to determine parcel points in real time 3D mapping of reconstruction projects, with 1cm accuracy on the ground, we could combine high resolution 3D satellite stereo models and precise drone photogrammetry.
Now we add 1 sec 1cm accuracy geodetic networking for Southeast Asian counties, such as Cambodia, Myanmar and Bangladesh, for land administration and cadastral projects in real time mode (FKP) and in seismic monitoring mode (GEONAP) for UN-GGRF initiative.

*G01-5-04
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Restoring the New Zealand Geodetic Datum after the 2016 Kaikoura Earthquake

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The 14 November 2016 magnitude 7.8 Kaikoura Earthquake and ensuing earthquake sequence resulted in widespread damage in the North Canterbury and Marlborough regions of the South Island of New Zealand. The earthquakes generated horizontal displacements of several metres and vertical displacements approaching 10 metres.

The deformation caused by these earthquakes needs to be incorporated in the New Zealand Geodetic Datum.

The datum includes a deformation model which accounts for both ongoing secular deformation and episodic earthquake related deformation. This enables a spatial reference system in which the coordinates of fixed ground marks are substantially constant over time despite the secular tectonic movement of the marks, thereby allowing the geospatial community to confidently combine and use spatial datasets from different epochs.

A challenge following earthquakes is to incorporate the resultant deformation into this datum in a timely way. Until this is done the datum does not provide a consistent spatial reference frame. Spatial data generated after the earthquake is likely to be out of terms with pre-earthquake data. Surveys conducted relative to local control marks may obtain significantly different coordinates depending on which marks are used.

The datum is updated using GNSS and InSAR data to derive models of the deformation caused by the earthquake sequence. Although the deformation model update is based on geophysical models of subsurface fault ruptures, the focus in building the model is to accurately reflect the surface deformation rather than accurately modelling the faulting.

The implementation of the model also needs to account for the needs and expectations of the geospatial community it serves. This may lead to different implementation methods in the near-field, where there is significant local relative movement, and in the intermediate and far field deformation, where the local deformation is predominantly translation.

*G01-5-05
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SHRF16: A Stable Houston Reference Frame for Faulting and Subsidence Study in the Houston Metropolitan Area, Texas, U.S. A.

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The greater Houston is one of the fastest-growing metropolitan areas in the United States. More than 150 historically active faults have been identified in the greater Houston area. Accumulated subsidence of over 4 meters during the past century has been observed in a large area of southeast Houston. Subsidence and faulting have caused moderate to severe damage to hundreds of residential, commercial, and industrial structures year by year in the Houston area. GPS technology had been employed in subsidence monitoring in the Houston area since the late 1980s. A dense GPS network with over 180 stations has been established in the Houston metropolitan area through a joint effort by the government, academic, and industry communities. One major consideration in determining the magnitude and velocity of ground displacement over time using GPS, particularly for horizontal ground deformations, is the selection of reference frames. GPS initially provides positioning with respect to a global reference frame. All sites are moving with respect to a global reference frame and site velocities are dominated by secular tectonic plate drifts. A local reference frame is needed to precisely interpret site specific ground deformations over time and space. In this study, we established a Stable Houston Reference Frame using public-available long-term (over 10 years) GPS observations as of 2016. Ten CORS adjacent to the Houston metropolitan area were used as common points (reference stations) to align SHRF16 with IGS08 at epoch 2012.0. The realization of SHRF16 is defined in terms of a Helmert transformation from the global reference frame IGS08. The main results from this study are the 14 parameters for reference frame transformation from IGS08 to SHRF16 and current subsidence contour map (2005 to 2016) in the Houston metropolitan area. SHRF16 will be incrementally improved and be synchronized with the update of IGS reference frame.

*G01-5-06
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Station calibration of the SWEPOS GNSS Network

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While the performance of positioning services are improved to the benefit of the users, with uncertainties from densified Network-RTK networks for construction work approaching the sub-centimeter level also in the vertical, the error sources related to the permanent reference stations (CORS) may soon be limiting factors for further improvement of performance.
Station dependent effects are thus important and limiting factors in high accuracy GNSS positioning. Electrical coupling between the antenna and its near-field environment changes the characteristics of the antenna from what has been determined in e.g. absolute robot or chamber calibration.

Since the first initial tests back in 2008, Lantmateriet together with Chalmers technical University and SP Technical research Institute of Sweden has carried out station calibration, in-situ calibration, of its network of permanent reference stations, SWEPOS. The station calibration intends to determine the electrical center of the GNSS antenna, as well as the PCV (phase center variations) when the antenna is installed at a SWEPOS station. One purpose of the calibration is to examine the site-dependent effects on the height determination in SWEREF 99 (the national reference frame). Another purpose is to establish PCV as a complement to absolute calibrations of the antenna-radome pair.

We will present booth the methodology for observation procedure in the field and the method for the analysis, together with results of the station-dependent effects on heights as well as PCV from the analysis. Some strength and weakness of our method for GNSS station calibration are discussed at the end.

*G01-6-01
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Foundation CORS: Underpinning a New Positioning Framework

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The Continuously Operating Reference Station (CORS) Network at the U.S. National Geodetic Survey (NGS) has provided improved coordinate determination to the National Spatial Reference System for 20 years. The CORS will become an integral part of the definition, realization and access starting 2022 when the NGS puts in place a new reference frame. The CORS Network consists of nearly 2,000 stations that are primarily owned and operated by other agencies and groups that provide their data to NGS for evaluation, archiving and use in position determination software such as the Online Positioning User Service (OPUS). The intent of the 2022 datum is that it be closely aligned with the most recent realization of the International Terrestrial Reference Frame in order provide consistency in the realization of positions in either the new US reference frame or in the ITRF. Pursuant to that, the NGS will be focusing on ownership or at least increased oversight of a sufficient number of stations to ensure that the ITRF is adequately tied to the new national datum. Priority is given to collocating with other techniques (e.g., VLBI) to enhance the linkage between the IGS solution and those of the other techniques when developing a future ITRF. Additional consideration will be to have a sufficient spatial coverage to ensure a sufficient spatial distribution to satisfy the national integrity of the NSRS. The intent is that these sites serve as the link to the ITRF and then serve to underpin any national reprocessing and stacking of regular CORS sites. In turn, derived positions from the CORS will lead to improved access to the NSRS for all geodetic applications.

ITRF2014/IGS14 European Regional Densification Using the EPN Long Term Daily SINEX product

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The successive realizations of the International Terrestrial Reference System are based on the analysis of space geodetic data series stemming from GNSS, SLR, VLBI and DORIS. Beyond the modeling refinements the realizations (called ITRFyy, where yy denotes the end date of data involved in the solution) includes growing data sets, therefore a gradual quality improvement of the consecutive solutions is expected.
On regional scale the geodetic reference frame realizations are maintained by densification of the global ITRS realizations using continental scale CORS networks. Such networks are operational in Europe (EPN), North-America (NAREF), South-America (SIRGAS), Africa (AFREF), Asia-Pacific (APREF).
In contrary to the present EPN practice, where weekly SINEX solutions are used, the European densification of IGS14 is being prepared based on the cumulative solution of the daily SINEX product series stemming from the EPN REPRO2 activity and the routine EPN data processing being done at 17 Analysis Centres.
As the cumulative solution is updated at each 15 weeks the agreement between the initial global frame solution and its regional densification series may vary in time as a consequence of new data added, due to changes in network geometry or in intermediate changes in modeling parameters.
In this paper the regional ITRFyy densification methodology is described and the European ITRF2014/IGS14 densification solution is introduced with special emphasis on testing the agreement level of the former IGb08 densification series and the IGS14 solution.

*G01-6-03
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Near real time modelling of coseismic and post-seismic deformation for NetworkRTK applications

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Deformation patterns that result from large earthquakes manifest as instantaneous coseismic and time-dependent post-seismic motion. For example, the deformation caused by the November 2016 Kaikoura Mw 7.8 resulted in coseismic displacements up to several metres while continuing post-seismic displacements have amounted to 20-30 cm after 3 months. Such events deform the geodetic infrastructure, which for the 2016 Kaikoura event, can be detected over 600 km from the epicenter.

Surveying applications, such as Network RTK, require precise relative and current epoch coordinates that are typically based on an International Terrestrial Reference Frame (.e.g. ITRF2008, ITRF2014). Although the latest ITRF realisation (ITRF2014) incorporates post-seismic decay for selected ITRF sites, commercial software that generates time-dependant coordinates assumes linear motion and cannot (currently) deal with non-linear motion. Abrupt changes in position i.e. coseismic displacement; are relatively easy to deal with – a new updated coordinate is computed. However, transient and non-linear motion such as that caused by post-seismic relaxation and slow slip events are more difficult to model and therefore predict.

Correcting the positions of NetworkRTK sites requires the development of low latency models of both the coseismic and post-seismic deformation. Traditionally dislocation models of earthquakes are available months or years after an earthquake but advances in instrumentation and processing algorithms means that models are available in near real time. As shown by the 2016 Kaikoura event, the post-seismic motion is evolving over time and therefore up to date positioning data is required to model the transient motion accurately. Although early models may not necessarily have the accuracies of the final models, it should be possible to make regular updates as additional data becomes available.

New Zealand Vertical Datum 2016, an improved gravimetric reference frame

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In June 2016 the New Zealand Vertical Datum 2016 (NZVD2016) was released. This quasigeoid based datum replaced the NZVD2009 and halved the nominal datum error from 6 cm to 3 cm.

The geoid underpinning NZVD2016 was improved through the acquisition of a nationally consistent airborne gravity dataset, re-analysis of the existing terrestrial database, and inclusion of of more recent satellite gravity data. The impact of each of these datasets is assessed and quantified before incorporation in the reference surface.

NZVD2016 also differs from NZVD2009 in the way that relationships to the 13 historical local vertical datums are managed. To ensure that the national datum is easily usable, NZVD2016 provides relationship surfaces to each local datum to facilitate the migration of data into the new reference frame. The computation and error characteristics of these surfaces are discussed, along with an analysis of the datum's performance in recent large earthquakes in New Zealand.

*G01-6-05
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The leveling net adjustment with a correction for altitude variations obtained from GNSS-based control stations data

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Geospatial Information Authority of Japan (GSI) has been maintaining longitude, latitude, and altitude of control points. As for the altitude reference system, we conduct leveling surveys all over Japan, the statistical calculation (net adjustment), and revise the altitude. However, the policy of administrative efficiency leads to a decrease in leveling survey distance. Thus, it takes more time to conduct surveys, and seems likely that gaps between calculated altitude and the current situation get larger because of crustal movement.
Since the 1990s, GSI has been developing GNSS Earth Observation Network System (GEONET). GEONET has two advantages: (1) observation stations exist uniformly, and (2) we can conduct a real-time observation. Focusing on these points, we investigated the potential to reduce the gaps of altitude by utilizing GEONET to correct altitude variations.
We conduct a new method for net adjustment as follows: (1) we apply curve fitting to GEONET time-series data to obtain altitude variations between the observation days for surveys and the reference day. (2) We apply Kriging method to create grid data of altitude variations for every observation day. (3) We apply bilinear method to estimate altitude variations by the grid data at each benchmark to correct relative elevations. (4) We conduct a net adjustment by using corrected relative elevations.
We evaluated the validity by comparing between altitude obtained by surveys and altitude estimated from GEONET data in the areas where we recently conducted surveys twice. From the studies, we found that (1) it was possible to estimate altitude with 1 cm accuracy on average, and (2) it was impossible to estimate local variation. These imply that we should compensate for GEONET's weakness. Fortunately, GSI has InSAR technique that has an advantage to detect local variation economically. If time allows, we will show the validation of Kumamoto earthquake with a combination of GEONET and InSAR.

*G01-6-06
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Precise leveling, tide gauge and satellite altimetry for definition of Saudi Arabia National Reference Frame (SANVRF) – Jeddah'2014

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Historically, in The Kingdom of Saudi Arabia several height reference systems have been developed and applied by different organizations. To unify the vertical reference frame of the Kingdom, the General Commission for Survey has developed and proposed for pre-definition a new national vertical reference frame (VRF) named Jeddah'2014. It is based on the new National Vertical Network (NVN), National Gravity Network (NGN), an analysis of 3.5 years of Tide Gauge Network data and an assimilation of all existing Satellite Altimetry (SA) data in the Red Sea and Arabian Gulf region.
A Wavelet Multi-resolution analysis (WMRA) of TG data residuals (after eliminating periodic tide effects) has been conducted for 11 TG stations in Red Sea and Arabian Gulf in order to determine the MSL, necessary for vertical datum definition of KSA. This analysis has been supported by almost 30 years of SA data and the most recent GOCE-based Global Geopotential Models (GGMs) for validation purposes. The final SANVRF has been defined following a Least-Squares Adjustments (LSA) of NVN geopotential numbers, assuming the height above Mean Sea Level (MSL) at Jeddah Tide Gauge Benchmark (JEDD-S) as fixed. With the high NVN leveling precision achieved the new KSA VRF will also form the base of the new precise KSA geoid model.
Details regarding the new SANVRF Jeddah'2014 are provided in this presentation, describing its conceptual and specific characteristics.

*G01-P-01
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Estimation of Post Seismic Deformation Model Using Monte Carlo Method

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The one of latest Global Geodetic Reference Frame (GGRF), ITRF2014 has been available since Jun. 2016. In ITRF2014, Post Seismic Deformation (PSD) models were newly introduced to improve accuracy of station coordinates impacted by major earthquake. PSD models will improve accuracy of coordinates of Japanese domestic GNSS observation network (GEONET) subject to active crustal deformation too. In this paper, we has developed Bayesian estimation method that based on ensemble Marcov Chain Monte Carlo (MCMC) method to make PSD models of GEONET station. This method can estimate PSD model stably avoiding local solution although PSD models includes non-linear functions. We compared estimated PSD model and that of ITRF2014 products in TSKB station, which is one of IGS GNSS station. As a result, we acquired s.d. of estimated PSD model and observation (E, N, U) = (10.1, 16.9, 1.7) mm. It is shown that estimated PSD model sufficiently explain observation data. We also evaluated prediction power of the PSD model in Miyako station, which has been impacted by the 2011 off the Pacific coast of Tohoku Earthquake. We estimated the PSD model of Miyako station with coordinate time series spanning two years from the earthquake (fitting period) and compare that PSD model with observation of post-fitting period. As a result, we found that their difference were smaller than 1cm for horizontal component, 2cm for vertical component at 2 years after the end of fitting period when Log+Exp+Log model was used.

*G01-P-02
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Impact of different TRF station coordinate parameterizations on VLBI combined EOP

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In the framework of the realization of the latest International Terrestrial Reference System, different solutions using different TRF station coordinate parameterization have been published. Namely, the DTRF2014, published by the German Geodetic Research Institute (DGFI-TUM), using a piece-wise linear station model with improved geophysical modeling, the ITRF2014, the official ITRF, using a piece-wise linear station model and an additional post-seismic deformation model, and the JTRF2014, published by Jet Propulsion Laboratory (JPL), using weekly estimations of station coordinates (epoch reference frames). The combination on the normal equation level of EOP and station coordinates is well established within the International VLBI Service for Geodesy and Astrometry and in cooperation with other space geodetic techniques (e.g. inter-technique combined TRF). In the combination process, the estimation of accurate a priori values for station coordinates plays an important role for the estimation of combined Earth Orientation Parameters (EOP). In our study we compare the impact on the routinely combined VLBI EOP by using the three different TRF solutions for a priori station coordinate estimation. The results of this study and the comparisons of the different solutions will be presented.

*G01-P-03
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Investigations on scale factor from VLBI observations

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The direct connection between the terrestrial and celestial reference frame as it is provided by the Very Long Baseline Interferometry (VLBI) technique makes possible to gain an insight into astrophysical and cosmological studies. One of potentially informative cosmology-oriented evaluation of VLBI astrometric surveys is based on the analysis of the scaling factor that is derived as a partial derivative of the observed group delay to the theoretical geometrical delay. If the observations would perfectly match the theoretical prediction, the scaling factor would be equivalent to unity. Otherwise, some deviation from unity can be detected. Our estimates from two independent software packages OCCAM and VieVS show that the scale factor from the VLBI measurements estimated for each radio source individually discloses a clear systematic aligned with the direction to the Galactic center-anticentre. Therefore, the radio sources located near Galactic anticentre may cause a strong systematic effect on the terrestrial reference frame, especially, in early VLBI years. Furthermore, we investigate a potential dependence of the scaling factor on the radio source redshift. We analyse geodetic VLBI observations carried out within the routine International VLBI Service (IVS) activity extended by selected sessions of the KVAZAR network.

*G01-P-04
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IGRS2013 Deformation Model: Linear Velocities and Co-seismic Deformation

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On October 11st, 2013, a new geodetic datum for Indonesia was defined by Geospatial Information Agency of Indonesia. The datum name is Indonesian Geospatial Reference System 2013 (IGRS2013). This is a semi dynamic datum which the reference epoch of geodetic control coordinate defined at 2012.0 and the change of coordinate due to plate tectonic motion and earthquakes should be accommodated by a deformation model. In this study we estimate a linear GPS velocities from time series coordinates starting from 1999 until end of 2016. We include also several earthquakes that have magnitude > M7 starting from 01 January 2000 until 12 December 2016 to estimate the co-sesimic deformation. Our estimate of linear velocities suggest that the GPS velocities shows the characterized of plate/block tectonic motion in the region. Moreover, our co-sesimic deformation suggest that most of Indonesia region affected by co-seismic deformation due to 2004 Sumatran-Andaman earthquake, 2005 Nias earthquake and 2012 Wharton Basin earthquake. The deformation model that consists a linear velocity and co-seismic deformation used to transform the coordinates from observation epoch to or from reference epoch of IGRS2013.

Keywords: Indonesia, IGRS2013, deformation model, linear velocities, co-sesimic deformation

*G01-P-05
IAG Symposium / IAG01. Reference Frames / G01. Reference frames

Investigating the performance of the GNSS-SLR co-location on-board GNSS satellites for reference frame determination

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The International Terrestrial Reference Frame (ITRF) is realized by combining data provided by four space geodetic techniques, namely the GNSS, SLR, VLBI and DORIS. Since the technique-specific ground networks do not share any common point, the combination requires some additional information establishing their reciprocal spatial distribution. In the current computation strategy, the inter-technique connection is provided by the so-called terrestrial ties which result from topometric surveys performed at those ITRF sites where the instruments of at least two different techniques are co-located. A possible alternative is provided by satellites equipped with the positioning payloads of different techniques. In principle, the co-location in space could overcome major limitations, such as, poor spatial distribution of ground local ties, their infrequent updates and their discrepancies with space geodesy estimates due to technique systematic errors. However, actual operational conditions are likely to impact the performance of the co-location in space and should be carefully assessed. In this study, we investigate the potential of the space ties on-board GNSS satellites for the realization of a homogeneous GNSS-SLR frame. We analyzed four years (2011-2014) of data collected by a ground network of about 100 GNSS receivers and 40 SLR stations. The computations were operated to determine long-term and quasi-instantaneous (9 days) reference frames. The resulting fully combined frames were compared to the GNSS-only and LAGEOS-only solutions in order to test the efficiency of the selected space ties in transferring frame information between the different subnetworks. The effect of possible future improvements in SLR tracking performances was also investigated by means of simulations. According to our results, the space ties on-board GNSS satellites do not realize, at present, a homogeneous GNSS-SLR frame.

*G01-P-06
IAG Symposium / IAG01. Reference Frames / G01. Reference frames

Developing a semi-dynamic datum for Nepal after the April 25 Gorka Earthquake

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Along with the damage to buildings and infrastructure, the April 25, 2015 Mw7.8 Gorkha earthquake caused significant deformation over a large area in central Nepal, with displacements of over 2 m recorded in the vicinity of Kathmandu. In order to correct the resulting distortions in the geodetic reference system, Nepal is in the process of introducing a new semi-dynamic datum that is aligned with ITRF2014 (epoch 2016.0). The new geodetic datum will incorporate a national deformation mode (NDM) that will have the capacity to correct for earthquake displacements as well as ongoing tectonic deformation associated with Nepal's location on the India/Eurasian plate boundary. The NDM discussed here contains models of the velocity field and both co-seismic and post seismic deformation for the Gorka earthquake plus co-seismic deformation for the Mw 7.3 12 May Aftershock. The velocity model for Nepal is based on a compilation of published velocity measurements from previous studies for Nepal and adjacent regions of China and India combined with new velocity estimates for the Nepal GNSS array stations. We have developed a preliminary velocity field by combining these studies and aligning them with the published ITRF2014 velocities for IGS stations. The co-seismic deformation associated with the Gorkha earthquake and its 12th May Mw7.3 aftershock are modelled using published dislocation models. In order to estimate the post-seismic relaxation, we used an exponential function with a uniform 43 day time constant. The model is implemented as a series of grid files allowing the secular velocities, co-seismic displacements for the April 25, 2015 Mw7.8 Gorkha earthquake and the 12th May Mw7.3 aftershock and the post-seismic relaxation coefficients for the Gorkha earthquake to be estimated. Using these grid files it is possible to estimate the deformation as a function of time for any point in Nepal and correct both survey measurements and coordinates to a common reference epoch.

*G01-P-08
IAG Symposium / IAG01. Reference Frames / G01. Reference frames

Assessment of displacement models used in time-dependent transformations. The particular case of California.

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The support of time-dependent transformations for surveying and GIS is becoming a critical issue. The main challenge is to calculate the accurate displacement of a station between two epochs. We focus on the uncertainties of station velocities used. In a first approximation, we use a global tectonic plate model to calculate point velocities. We show the impact of the velocity model on the coordinate accuracies.

Several countries, particularly in active regions, are developing semi-dynamic reference frames. These frames include local displacement models updated regularly and/or after major events (such as earthquakes). We study the particular case of California and the Horizontal Time-Dependent Positioning model developed by the NGS. We show it improves greatly accuracy of estimated displacements.

The integration of these local deformation models into surveying or GIS applications is an upcoming challenge. We want also to encourage the geodetic community to develop and use standard formats.

*G01-P-09
IAG Symposium / IAG01. Reference Frames / G01. Reference frames

Verification of accelerated vertical crustal movements in the Tohoku region prior to the 2011 Tohoku-Oki earthquake by reanalysis of GEONET data using Precise Point Positioning

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Homogeneous coordinate time series data over a decade from GNSS analysis is essential for investigation of various phenomena preceding massive earthquakes such as the Tohoku-Oki earthquake. Kurokawa (2016) found a significant difference between vertical velocities obtained from GNSS and those from tidal record during 2003~2011. This suggests that the long-term homogeneity of the GNSS result is questioned. Routine processing of GEONET, the GNSS continuous observation network in Japan, currently adopts the network analysis strategy (F3 solution). However, such strategy may generate bias in analysis result because the combination of baselines has changed in response to the increase of the number of stations. In this study, we reanalyze the daily coordinate of 30 GEONET stations along the coast of Tohoku region for the last 20 years by using Precise Point Positioning method (PPP) in order to get rid of bias due to network analysis. We compare the velocities obtained from the F3 solution and our PPP result. In the horizontal components, the differences are about 1~1.5 mm/yr before the Tohoku-Oki earthquake. In the vertical component, large differences of about 2~3 mm/yr are found before 2003, and gradually decrease to smaller than 0.5 mm/yr just before the Tohoku-Oki earthquake. Even if the difference is small, there exist systematic differences in many cases. We estimate the vertical acceleration before the Tohoku-Oki earthquake. Our PPP result shows no significant change along the Japan Sea coast, and accelerated subsidence along the Pacific coast (about -0.3 mm/yr^2). This result is consistent with the horizontal acceleration indicated by Mavrommatis et al. (2014) and the accelerated subsidence by Kurosawa (2016). Furthermore, this suggests that the construction of a network for the F3 solution is one of the causes of the common mode error, because Mavrommatis et al. (2014) and Kurokawa (2016) eliminated such errors by using spatial filtering technique.

Modeling vertical displacements at stations of the Geocentric Reference System for the Americas (SIRGAS) due to hydrological load

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The usual assumption of constant station velocities in reference frame realizations has proved to be inefficient for many sites where geophysical processes cause significant non-linear motions, either seasonally (e.g., due to oceanic, hydrological or atmospheric loads) or episodically (e.g., due to co-seismic and post-seismic processes). Seasonal displacements are usually described using harmonic functions with annual and sub-annual periods. This work presents an alternative description based on the modelling of the hydrological process underlying the seasonal displacement. The study focuses in a first stage on the vertical displacements of the SIRGAS stations associated with the seasonal variations of the hydrological load. The developed methodology combines two sources of information: GNSS normal equations of the SIRGAS network (NEQ) to describe the geometric displacements; and monthly grids of equivalent water height (EWH) provided by GRACE to describe the hydrological load. The proposed model relates the response of the Earth's crust to the hydrological load and relies on a numerical solution of the static equilibrium equation for an elastic medium (i.e. the Earth's crust) characterized by an 'elastic parameter', which results from the combination of the Poisson ratio and the Young modulus. The NEQ are calculated on a weekly basis and remain weakly constrained to avoid deformations of the network geometry. These equations are then combined with the EWH values and some fiducial station positions are constrained to define the datum of the network. This leads to a common adjustment of 7 parameters per station, namely: 3 positions at a certain epoch, 3 velocities, and 1 elastic parameter. The vertical positions calculated after the adjustment agree with the weekly vertical positions published by SIRGAS within +/- 3 mm at the one sigma level, which is interpreted as a first satisfactory evaluation of the method here presented.

*G01-P-11
IAG Symposium / IAG01. Reference Frames / G01. Reference frames

SIRGAS: the core geodetic infrastructure in Latin America and the Caribbean

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Studying, understanding, and modelling geophysical phenomena, such as global change and geodynamics, require geodetic reference frames with (1) an order of accuracy higher than the magnitude of the effects we want to study, (2) consistency and reliability worldwide, and (3) a long-term stability. The definition, realisation and maintenance of the ITRS are oriented to guarantee a globally unified geometric reference frame (i.e., the IRTF) with reliability at the mm-level. The densification of the global ITRF in Latin America and The Caribbean is given by SIRGAS (Sistema de Referencia Geocentrico para Las Americas), primary objective of which is to provide the most precise coordinates in the region. At present, SIRGAS is the backbone for all regional projects based on the generation, use, and analysis of geo-referenced data at national as well as at international level. Besides providing the reference for a wide range of scientific applications such as the monitoring of Earth's crust deformations, vertical movements, sea level variations, atmospheric studies, etc., SIRGAS is also the platform for practical applications such as engineering projects, digital administration of geographical data, geospatial data infrastructures, etc. However, the reliability of SIRGAS as reference frame is being affected by the frequent occurrence of seismic events deforming the geometry of the network and by the omission of non-lineal station movements including systematic errors in epoch coordinates. In this context, this presentation summarises the main challenges faced currently by SIRGAS: (1) A high-resolution monitoring of the reference frame deformation by means of more reference stations and improved analysis standards; (2) Co-seismic deformation models for the transformation of station positions between pre- and post-seismic frame realisations; (3) Reliable modelling of non-lineal station movements in the reference frame computation to improve the estimation of epoch coordinates.

*G01-P-13
IAG Symposium / IAG01. Reference Frames / G01. Reference frames

IDS DORIS analysis centre Geodetic Observatory Pecny: development and research

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Geodesy Observatory Pecny (GOP) provides one of the International DORIS Service (IDS) analyses centers, participating on the combined IDS products including the solution for ITRF2014. As the unique approach, GOP employs a DORIS-developed version of the Bernese GPS Software. Besides the routine operating, the recent research focuses on several topics as preprocessing strategy and observation weighting, estimation of Earth rotation parameters, station clock modeling from the DORIS/pseudorange measurements, satellite attitude modeling and orbit parametrization. We demonstrate that observation weighting cos (Z) reduces the scale bias respect to ITRF2014 by about 3 ppb. Combination of this observation weighting and new preprocessing strategy has significant positive impact on the station repeatability and weekly station RMS with respect to DPOD/ITRF, as well as on the precise orbit determination.

*G02-1-01
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Rectangular rotation of spherical harmonic expansion of arbitrary high degree and order

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In order to move the polar singularity of arbitrary spherical harmonic expansion to a point on the equator, we rotate the expansion around the y-axis by 90 degrees such that the original x-axis becomes a new pole. The spherical harmonic expansion coefficients are transformed by multiplying a special value of Wigner's D-matrix and a normalization factor. Thanks to the choice of not the x- but the y-axis as the rotation axis, the special value becomes a real-valued function: Wigner's d-function of the angle as 90 degrees. Its realness results the transformation of Cnm and Snm completely separated. The transformation matrix is unchanged whether the coefficients are fully-normalized or Schmidt quasi-normalized. This is because the rotation is restricted within the coefficients of the same degree, and therefore the difference in the normalization factors do not alter the transformation formula. The d-function is stably computed by an increasing-degree fixed-orders three-term recurrence formula. The two seed values can be also computed recursively. The underflow problem during the recursions is effectively resolved by the so-called X-number formulation (Fukushima, 2012, J. Geodesy, 86, 271--285). As an example, we obtained 2190x2190 coefficients of the rectangular rotated spherical harmonic expansion of EGM2008. The obtained coefficients are of the 15 digits consistency with the original one because the transformation is conducted by the quadruple precision X-number formulation. A proper combination of the original and the rotated expansions is realized by switching them at the parallels of 45 degrees latitude. The combined spherical harmonic expansions will be useful in (i) integrating the polar orbits of artificial satellites precisely, and (ii) synthesizing/analyzing the gravitational/geomagnetic potentials and their derivatives accurately in the high latitude regions including the arctic and antarctic area.

*G02-1-02
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Gravitational contribution of a spherical tesseroid by means of mapping it into sectors of spherical band

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We present a new methodology for computing the gravitational effect of a spherical tesseroid, based on the rotation from the global Earth-Centred Rotational reference frame to the local Earth-Centred P-Rotational reference. After rotation, the gravitational effect of the tesseroid is computed via the effect of a sector of spherical zonal band. In this respect, two possible procedures to handle the rotated tesseroids have been proposed and tested, one based on the re-orientation of the rotated tesseroids, and the other based on a second-order tesseroidal decomposition. Sensitivity tests show that the RT procedure is adequate in estimating the gravitational effects at distances greater than 0.1 degree from the computation point; the more accurate ST procedure is required at closer distances. The implemented procedure has been tested against other methods known in literature. In particular, benchmark tests have been carried out with respect to the methods proposed by Heck and Seitz (2207), Hirth and Kuhn (2014) and Uieda et al. (2015). The comparative analysis showed that the new devised methodology is in good agreement with all the above-mentioned methods and can be thus used within future more general benchmark studies.

*G02-1-03
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Boundary complexity in classical and variational concepts of solving geodetic boundary value problems

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In gravity field studies the complex structure of the Earth's surface makes the solution of geodetic boundary value problems quite challenging. This equally concerns classical methods of potential theory as well as modern methods often based on a (variational or) weak solution concept. The aim of this paper is to seek a balance between the performance of an apparatus developed for the surface of the Earth smoothed up to a certain degree and an iteration procedure used to bridge the difference between the real and smoothed topography. The approach is applied to the solution of the linear gravimetric boundary value problem in geopotential determination. Within the classical concept a transformation of coordinates is used that offers a possibility to solve an alternative between the boundary complexity and the complexity of the coefficients of the partial differential equation governing the solution. Also the oblique derivative boundary condition is taken into account in this way. The use of modified spherical and also modified ellipsoidal coordinates is discussed. The complexity of the boundary is reflected in the structure of Laplace's operator. Green's function representation is applied and the structure and convergence of the iteration steps is analyzed. The weak solution concept has different features. The aim here is to simplify the bilinear form that defines the problem under consideration and to justify the use of Galerkin's matrix constructed for an approximation solution domain. The approach focuses on the use of a sphere or an ellipsoid of revolution in quality of an approximation boundary. Also in case of the weak solution the simplification is compensated by successive approximations. The related functional analytic and numerical aspects are discussed. In both the cases attention is also paid to the question concerning the possible (hidden or explicit) role of analytical continuation.

*G02-1-04
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

MRR and LSC – A mutual benefit for advanced regional gravity field modeling

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Various regional gravity field modeling approaches exist next to each other – everyone revealing individual strengths and weaknesses depending on the methods themselves and on the fields of application. For instance, in order to establish precise height systems in developing countries with sparse data availability and/or low-quality, Multi-Resolution Representation (MRR) using spherical basis functions and Least Squares Collocation (LSC) are suitable approaches. Drawing mutual benefit from both is the innovative key aspect of our study and enables an advanced modeling of the gravity field in the specific regions by optimally combining heterogeneous data sets.

The common theoretical base of MRR and LSC is that in- and output functionals are described by series expansion in terms of Legendre Polynomials. For formulating observation equations, LSC incorporates full covariance information of the observations, and thus, provides coherent error estimates of the resulting models; MRR manages a well-balanced relative weighting of heterogeneous input data by variance component estimation, and a consistent spectral combination by appropriate filtering.

We study in detail the differences of LSC and MRR, learn from each other and finally bring together the strengths of both approaches: by (1) matching the mathematical fundamentals, (2) analyzing closed-loop scenarios with simulated data, and finally (3) setting up an optimal regional modeling strategy. We focus on a study area in South America with different topographic features and combine heterogeneous data sets obtained in varying measurement heights and with different quality, spectral and spatial resolutions. From the findings of these comprehensive studies, we plan to derive a generalized concept which provides developing countries the opportunity of establishing physical height systems. Those have a high socio-economic impact for various applications in science, infrastructure and administration.

*G02-1-05
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Properties and applications of gravity-field curvatures in geodesy

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Recently reported developments in experimental physics suggest that gravity-field curvatures could become observable one day through, e.g., atom interferometers or satellite constellations. This contribution reviews basic properties of these functionals of the gravity potential (third-order directional derivatives) and discusses their possible applications in geodesy given their signal-to-noise-ratio reaches an acceptable value in order to facilitate these small values in geodetic applications. Discussed issues include spectral and stochastic properties of Earth's gravity-field curvatures given currently available geopotential models, links to other commonly used gravity-field parameters in geodesy, and applicability for local and global gravity field modelling.

*G02-1-06
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Direct topographical effect on the airborne gravity disturbance for Helmert's second method of condensation

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Helmert's second method of condensation removes the topographical mass and compensates using a thin mass layer on the geoid, transforming the Earth's gravitational potential to a harmonic field in the space between the geoid and topographical surface. Consequently, the Helmert(ized) gravity anomaly can be continued from the Earth's surface downward to the geoid to meet the requirement of Stokes's integral for the determination of the geoid in the harmonic Earth's gravity field. Finally the geoid can be determined by restoring the topography from the Helmert mass layer. In this process, the Helmert gravity anomaly is determined from the Molodensky-type free-air anomaly by evaluating and correcting for the direct and second indirect topographical effects (DTE and SITE) on the Earth's surface. The Molodensky-type anomaly is defined by the difference between the gravity value at a point on the Earth's surface and the normal gravity at the corresponding point on the telluroid. This approach is suitable when the gravity observation and orthometric/normal height are available on the Earth's surface. The airborne gravity observations provide the gravity disturbance, as ellipsoidal height is generally measured at flight level. To apply Helmert's second method of condensation to the gravity disturbance, only the direct topographical effect is required at flight level. In this paper, we first formulate the direct topographical effect on the gravity disturbance at flight level in terms of both Newton's integral and spherical harmonic series, then numerically determine the requirements on spatial and spectral resolutions of digital elevation model (DEM) for the evaluation of DTE at various flight levels.

*G02-2-01
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Closing the GOCE polar gap in Antarctica from airborne gravity and derived gravity gradients

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GOCE has mapped the global gravity field with hitherto unprecedented accuracy and resolution, except for the polar gaps north and south of latitude 83.3 degree. While the Arctic gap has been filled since a decade by Arctic Gravity Project data, filling the Antarctic polar gap has been a major challenge. An ESA-supported airborne gravity survey was carried out to do this in a major, challenging field campaign 2015/16. This “Polar Gap project" used a Twin-Otter aircraft equipped with several gravity sensors (spring gravimeter and iMAR IMU), magnetometers, ice penetrating radar, and scanning lidar, to collect a complete suite of airborne remote sensing data over the essentially unmapped region of the polar gap. The PolarGap logistics involved two deep interior field camps, as well as flights the Amundsen-Scott South Pole station, thanks to a special arrangement with NSF. In the talk we outline the Antarctic field operations, and show final results of the campaign, including performance of the gravity sensors, the gravity reference network, and the comparison to the limited existing gravity data in the region. We also show results of computations of gravity field gradients at altitude, computed by least-squares collocation, and compared to GOCE gradients along the outer rim of the polar gap. Examples of other acquired geophysical and lidar data are also given, including discoveries of hitherto unknown major subglacial valleys and mountains in the survey region.

A Comparison of Airborne Vector Gravimeter Measurements with the NOAA Geoid Slope Validation Survey 2014

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Gravity measurements made from aircraft are becoming widely used in combination with satellite and terrestrial data for geoid computation. At present, only measurements of the vertical component of the gravity vector are used for this purpose. Incorporation of the horizontal components of the vector offers the opportunity to strengthen the geoid solution, and minimize edge effects at the survey boundaries. Most airborne gravity meters do not offer the possibility of measuring all three components of gravity, however the AIRGrav system developed by Sander Geophysics has shown the ability to routinely obtain repeatability at the sub-milliGal level, with suitable processing.

This presentation will focus on a direct comparison of airborne measurements flown on a repeat track over the GSVS2014 test line located in Iowa, USA. The high-accuracy GSVS2014 ground data will be upward continued to the flight elevation for comparison with the measured airborne gravity components (equivalent to magnitude and deflection of the vertical). The airborne data will also be compared with the latest gravity models, including EGM2008, EIGEN6c4, and the current NOAA model xGEOID17. The vector airborne data will also be incorporated into a gravity model to assess their contribution.

*G02-2-03
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Evaluation of the contribution of optical clocks to gravity field modelling

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In the past decade, the performance of optical clocks and frequency transfer techniques have been largely improved. These technical developments allow to measure relative frequency differences with an inaccuracy of 1 x 10^-18 in the near future. According to the formula of relativistic gravitational redshift, the frequency difference can be transformed to a geopotential difference with an error of 0.1 m^2/s^2, i.e. approximately 1 cm in terms of height changes. Hence, optical clocks present a new and promising technique for determining the Earth's gravity field and related quantities.

In this context, the present work aims to evaluate the contribution of optical clocks to gravity field modelling in a combined analysis of different types of gravimetric observations. Here, gravity anomalies, gravity gradients and potential differences are used for a simulation study, taking Germany as a test case. With this simulation study, we attempt to answer the following research questions: 1) How much can optical clocks help improving gravity field recovery? 2) How many clock measurements are required to improve a combined gravity field model? 3) How should a clock network be arranged to achieve an optimal gravity field solution?

*G02-2-04
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Cold Atom Interferometers Used In Space (CAIUS) for measuring the Earth's gravity field

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In the past decades, it has been shown that atomic quantum sensors are a newly emerging technology that can be used for measuring the Earth's gravity field. Whereas classical accelerometers typically suffer from high noise at low frequencies, Cold Atom Interferometers are highly accurate over the entire frequency range.
There are two ways of making use of that technology: one is a gravity gradiometer concept, which relies on a high common mode rejection that relaxes the drag free control compare to GOCE mission; and the other one is in a low-low satellite-to-satellite ranging concept to correct the spectrally colored noise of the electrostatic accelerometers in the lower frequencies. We will present for both concepts the expected improvement in measurement accuracy and for the gravity gradiometer concept the expected improvement of Earth gravity field models, taking into account the different type of measurements (e.g. single vs. 3 axis, integration time, etc.) and different mission parameters such as attitude control, altitude of the satellite, time duration of the mission, etc.

*G02-2-05
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

An innovative tool for marine Gravimetry: results of a survey with a cold atom gravimeter

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Measurements of marine gravimetry are usually carried out by relative shipborne gravimeter. We present the development and the tests of an absolute onboard gravimeter for marine applications that highlights a real technological breakthrough. This instrument is based on the measurement of the acceleration of a cloud of cold atoms in free fall with an atom interferometry method. This technology has already shown excellent performances for static gravimeters and compares favorably with the best classical mechanical absolute gravimeters. Here the challenges were to develop a cold atom gravimeter able to measure gravity in a mobile platform where the gravimeter is subject to accelerations and rotations. For this purpose, the sensor head has been miniaturized and placed in a gyrostabilized platform. The gravimeter has also been adapted to work with strong vibrations and accelerations which occur in a ship. We report the gravity marine survey realized by strong swell and bad weather in the bay of Biscaye during the winter 2015-2016. After laboratory tests, the prototype has been successfully tested on the French Shom N/O vessel " Beautemps-Beaupre " during two campaigns of few days and compared to the commercial spring marine gravimeter KSS32-M. We present the results and the benefit of such a technology for marine surveyors.

Development of a high-accuracy gravity measurement system onboard a moving autonomous underwater vehicle

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We have developed an underwater gravity measurement system onboard the autonomous underwater vehicle (AUV) Urashima (JAMSTEC). The gravimeter is mounted on a gimbal unit and housed in a pressure-proof sphere vessel made of titanium alloy. The gravity sensor is kept at a constant temperature of 60.4 degree C and covered with a sheet of permalloy for magnetic shielding. In order to obtain precise gravity data, a Gaussian low-pass filter with the width of 100-300 s is applied to 100 Hz output of the gravity sensor, and corrections are made using various measurements: correction of vertical acceleration with high-accuracy water pressure gauge data, Eotvos and free water corrections with the AUV's navigation data, correction of location difference between the gravimeter and water pressure gauge with the AUV's pitch and roll angle data, and Bouguer correction with the detailed topographic data collected by the Urashima's multi-beam bathymetric system. A detailed and high-accuracy gravity survey of seafloor mineral deposit area can be carried out by moving the AUV along planned track lines 50-100 m above the seafloor. After the first successful sea experiment in September 2012, good quality data were collected by three experiments in mineral deposit areas in the Okinawa Trough and the Izu-Ogasawara Arc. Almost noiseless gravity anomalies were obtained by the above data processing of the collected data including those from constant altitude track lines above rough seabottom topography, where large amplitude vertical acceleration was observed. We obtained a good result with an rms crossover error of about 0.1 mGal in a favorable survey condition: measurements at a constant depth of 1550 m in relatively flat Izena Caldera of the Okinawa Trough. High anomalies with amplitudes < a few mGal, which suggest occurrences of high-density material, possibly mineral deposits, are observed in the Bouguer anomaly map of the southern part of Izena Caldera.

An improved gravimetric geoid model for Japan based on the Stokes–Helmert scheme with a deterministically modified Stokes' kernel

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This study developed an improved gravimetric geoid model for Japan on a 1 * 1.5 arc-minute grid, based on the remove–compute–restore with Helmert's second method of condensation (the Stokes–Helmert scheme). A GOCE (the Gravity field and steady-state Ocean Circulation Explore)-related global geopotential model was used with 309,992 land gravity data and an updated altimetry-derived marine gravity model. To minimize the truncation error and appropriately combine each gravity data, the hybrid Meissl–Molodensky modified spheroidal kernel was employed with modification parameters regionally tuned. Thus, we created a gravimetric geoid model for Japan corresponding to GNSS/leveling geoid heights with a standard deviation of 5.91 cm, an improvement of 2.63 cm compared with the previous model (JGEOID2008). This remarkable improvement was particularly evident in the long-wavelength component of the geoid undulation. The north–south tilted trend of the difference between the gravimetric and GNSS/leveling geoid heights was reduced significantly from 0.18 to 0.06 ppm. Gravimetric geoid model improvements provide the possibility of generating a new standard and convention for the height reference system in Japan, currently realized by spirit leveling and tide-gauge observation.

*G02-3-02
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

AFRGDB_V2.0: The Gravity Database for the Determination of the Earth's Mathematical Surface in Africa

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In the framework of the activities of the IAG sub-commission on the gravity and geoid in Africa, it is needed to have a uniform gridded gravity data set to determine the earth's mathematical surface (the geoid) in Africa using Stokes' integral in the frequency domain. The available gravity data set consists of land point gravity data as well as shipborne and altimetry derived gravity anomalies data. The available gravity data set has a lot of significant gaps, while in some particular areas the distribution is very dense, besides the fact that the shipborne and altimetry data have a line structure (along tracks). This leads to a problem in determining a reasonable empirical covariance function, and consequently reduces the capability of the used least-squares prediction technique. Filtering the available gravity data and degrading the ocean gravity data took place to overcome this problem. The establishment of the gravity database for Africa has been carried out using an iterative process employing an ultra high-degree tailored reference model and weighted least-squares prediction technique. The land gravity data got the highest precision, while the shipborne and altimetry gravity data got a moderate precision. In each iteration step, the data gaps are filled with the ultra high-degree tailored reference model computed at the previous iteration step, getting the lowest precision within the prediction technique. The weighted least-squares prediction technique is thus carried out to estimate gridded gravity anomalies, which are used to estimate a new ultra high-degree tailored reference model employing a least-squares harmonic analysis technique. The iterative process continues till the solution stabilizes. The AFRGDB_V2.0 gravity database on a uniform 5' x 5' grid has been established by the developed process. The precision of the developed gravity database is tested. A comparison with the previous AFRGDB_V1.0 is made and extensively discussed.

*G02-3-03
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Terrestrial gravity data for a new Russian quasigeoid model

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A new quasigeoid model for Russia is planned to be calculated in the next few years.
For this purpose the gravity database was created from the geological gravity surveys which were carried out from the late 1940s to the 2000s. This means there are on the average 0.1-0.25 points per squared kilometre with an accuracy of the Bouguer anomalies 0.8-1.0 mGal. Usually, but not always, each gravity point has geodetic coordinates, the normal height, the free-air anomaly, the Bouguer anomaly with a density of 2.3 g/cm^3, the refined Bouguer anomaly with a density of 2.67 g/cm^3 and the terrain correction. These values are strictly related to each other and can be easily checked for inconsistencies and errors, but unfortunately they don't cover the whole Russian territory, because not all the surveys were digitized yet.

In 1980th the mean Bouguer (with a density of 2.67 g/cm^3) and the Faye gravity anomalies with the resolution of 5'x7.5' were calculated directly from the gravity maps for the whole USSR territory and around its borders. These gridded data are almost complete for the whole area, but they have not been evaluated since the creation, which is done in this work by comparing them with the database points and the global gravity field models.

The new gridded Bouguer anomalies for Russia were created with GMT software by concatenating after gridding the point database with the old grid data to fill-in the gaps. The Faye anomalies were derived by subtracting the Bouguer plate reduction calculated with the RuDTM2014 digital elevation model.

DRUKGEOID15: The new geoid of Bhutan

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In this research we present a new regional geoid for Bhutan, a land-locked country in the Himalayas. For this mountainous area only few terrestrial gravity data are available which can explain the metre level differences for this region between two recent global geopotential models: EGM2008 and EIGEN-6C4. To improve this situation, a new terrestrial gravity campaign was performed from November 2014 to May 2015. In total 255 new gravity points were observed together with their coordinates using GPS using two SCINTREX CG5 gravimeters.
Using the standard remove and restore technique, together with the residual terrain correction a new regional geoid, called DRUKGEOID15, was computed. EIGEN-6C4 together with the Shuttle Radar Topography Mission (STRM) digital terrain model a smooth residual gravity field was obtained in the remove step. Using standard least-squares collocation, this was converted into a residual height anomaly field after which the effect of EGM2008 and the terrain model on the height anomalies were restored. The height of the mountains can reach five kilometres which causes the height anomaly to geoid corrections to reach values of a few metres. Furthermore, we demonstrate that the height anomaly to geoid corrections provided by the EGM2008 model differ up to one metre with our more refined computed values following the method of Flury and Rummel (2009). Finally, we present a comparison of our geoid with orthometric heights observed at benchmarks that also were observed with GPS, demonstrating the improved accuracy of the new regional geoid compared to EGM2008 and EIGEN-6C4.

*G02-3-05
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Combining airborne and terrestrial gravity data to improve the geoid model in Brazil

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Brazil is a country of continental proportions and with different geographic characteristics. From its coast of nearly 7,400 km, where it houses 25% of the population, up to the 5,500,000 km² that form the Amazon region, this country has great challenges for Geodesy. One of these challenges is linked to the improvement of the geoid model quality to meet the needs related to the areas of knowledge, besides having homogeneous geoid undulation precision in most of the Brazilian territory. The country has about 450,000 ground gravimetric stations. While the South and Southeast regions have a regular distribution, the North (Amazon) and Northeast regions lack terrestrial gravimetric data. In this sense, this work aims to combine terrestrial and airborne gravity data to improve the Brazilian geoidal model. Two areas were selected. The first is bounded by 20S and 24S in latitude and 48W and 54W in longitude and has terrestrial and airborne gravity data. The second area is located in the Amazon region and is limited by 05N and 05S in latitude and 50W and 75W in longitude and does not have regular distribution of terrestrial data, only airborne data. The computation are being conducted using the GRAVSOFT package. The geoid models computed were based on EIGEN-6C4 up to degree and order 200 as a reference field. The oceanic region was completed with the mean free-air gravity anomalies derived from a satellite altimetry model from the Danish National Space Center, called DTU10. The short wavelength component was estimated via FFT. It is expected that the result will be aggregated to the calculation of the new Brazilian geoid model predicted for 2018.

*G02-3-06
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

The gravimetric component of AUSGeoid2020 and its error model

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As Australia is moving from the Geocentric Datum of Australia 1994 (GDA94) to the new datum GDA2020, a new accompanying quasigeoid model has been computed: AUSGeoid2020. The 2020 designation is because ITRF velocities have been used to predict the location of the datum so as to prolong its useful life. Like its predecessor AUSGeoid09, AUSGeoid2020 is built up of a gravimetric quasigeoid model that has subsequently been distorted to fit the Australian Height Datum (AHD) using cross-validated least-squares collocation. AUSGeoid2020 includes many improvements over AUSGeoid09 including use of new data and improved numerical integration routines. Another major improvement is that AUSGeoid2020 is accompanied by an error model with geographic specificity, so that users no longer need to rely on crude error estimates taken from a single nationwide comparison to GNSS-levelling data. The error estimates are propagated from uncertainties in the GNSS-levelling, terrestrial and altimeter-derived gravity anomalies and gravimetric terrain corrections. This presentation outlines the development of the gravimetric component of AUSGeoid2020 and its associated errors. Results of various numerical tests used to optimise the model are shown. Special emphasis is placed on the influence of data uncertainty on quasigeoid error estimates. The model is validated through comparison to ˜7,000 GNSS-levelling data and ˜1,000 historical deflections of the vertical, showing the error propagation to be realistic.

*G02-4-01
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

NGS Annual GRAV-D enhanced Geoid Models – xGEID2017: What is new and the results

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The United States National Geodetic Survey [NGS] has been computing experimental gravimetric geoid models annually. For these models, the latest satellite gravity models are combined with terrestrial gravity data, and with airborne gravity data collected through the “Gravity for the Redefinition of the American Vertical Datum" [GRAV-D] effort over the USA and its territories. To date, over 50% of this area has been flown. Both the airborne and terrestrial gravity data are cleaned and their accuracies are estimated for combination in the least squares sense. This paper outlines the methods used for data cleaning, editing and error estimation, and the data combination. Results from using independent data sets to validate the geoid models are also presented.

*G02-4-02
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

High-resolution modelling of the static gravity field from the GOCE gravity gradients using meshless boundary collocation techniques

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Meshless boundary collocation techniques like the method of fundamental solutions (MFS) or singular boundary method (SBM) can be efficiently used to model the static gravity field purely from the GOCE gravity gradients. These numerical methods use the fundamental solution of the Laplace equation as basis functions. Hence, the system matrix is created by the second radial derivatives of the fundamental solution that depend solely on geometrical parameters, i.e. on 3D positions and direct distances between the GOCE observations and source points located on the Earth's surface. Such a configuration is free of singularities and MFS can be applied to derive unknown coefficients in the source points. From these coefficients the disturbing potential and gravity disturbances can be evaluated in any point above the Earth's surface. To obtain their values directly on the Earth's surface, e.g. at the source points, SBM can be applied. The key idea of SBM is to isolate singularities of the fundamental solution and its derivatives using some appropriate regularization techniques.
The numerical experiments present results of processing several datasets of the GOCE measurements, each for a different semi-annual period. To obtain "cm-level" precision, the source points are regularly distributed over the Earth's surface with the high-resolution of 0.05 deg (12,960,002 points). For every dataset the disturbing gravity gradients as input data are filtered using the nonlinear diffusion filtering. Large-scale parallel computations are performed on the cluster with 1.2 TB of the distributed memory. A combination of numerical solutions obtained for different datasets/periods yields the final static gravity field model which is compared with the SH-based satellite-only geopotential models like GO_CONS_GCF_2_DIR_R5. Finally, the geopotential evaluated on the DTU13 mean sea surface model is used to derive velocities of the ocean geostrophic surface currents.

*G02-4-03
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Satellite gravimetry from tracking: do it right, and for better

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Satellite gravimetry from tracking has played a key role in precise recovery of global Earth's gravity models. In this talk, (1) We will prove that the standard numerical integration method to reconstruct a precise global Earth's gravity model from satellite tracking measurements, as currently used to produce almost all standard global Earth's gravity models by major institutions worldwide (NASA Goddard Space Flight Center, GFZ, JPL and University of Texas CSR, for example), is incorrect mathematically; (2) Bearing in mind that gravity satellites can be precisely tracked almost continuously by using global navigation satellite systems, we develop a new, measurements-based perturbation method for precise reconstruction of global Earth's gravity model from satellite tracking measurements. This new measurement-based perturbation method is uniformly convergent from the mathematical point of view for arcs of any length and can theoretically extract any small forces from long arc measurements with a very high resolution; (3) We develop three different local solutions to the Newton's nonlinear different differential equations of satellite motion. As a result, the new solutions can serve as starting foundations for global satellite gravitational modelling from satellite tracking measurements; and finally, (4) By directly turning the nonlinear differential equations of satellite motion into the nonlinear integral equations, and recognizing the fact that satellite orbits can now be measured almost continuously at the level of random errors, we further reformulate the links between satellite tracking measurements and the global uniformly convergent solutions to the Newton's governing differential equations as a condition adjustment model with unknown parameters. With all the efforts, we have finally constructed solid mathematical foundations for the next generation of global satellite gravitational models of high precision and high resolution.

*G02-4-04
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Evaluation of Dynamic Heights on the Great Lakes

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The National Geodetic Survey (NGS) supports the Center for Operational Oceanographic Products and Services (CO-OPS) in the maintenance and access to the International Great Lakes Datum of 1985 (IGLD 85). IGLD 85 is expressed as a dynamic height and is informally considered as a height equivalent (based on work to raise a unit mass) above mean sea level. IGLD 85 is also based on an adopted elevation at Point Rimouski/Father's Point as well as mean water levels at a set of master water level stations on the Great Lakes. Due to various observational, dynamical, and steric effects, there will be slight departures between a dynamic height and an IGLD 85 height. These departures are known as hydraulic correctors and can range from a few cm's to a couple dm's. With cm-level accurate orthometric heights planned as a part of the new US datums in 2022, an update to the dynamic height datum for the Great Lakes is also planned. This paper focuses on assessment of the accuracy of the current experimental geoid height models for use in developing updated dynamic heights. Fourteen CORS sites and an additional 39 water level sites occupied by campaign GPS were evaluated. The GPS-derived geometric coordinates were transferred via second order leveling to the 53 water level stations that continuously monitor the Great Lakes. Using the geometric coordinates for the mean water level surfaces, a geopotential model was applied to determine dynamic heights for comparison around each Lake. The CORS sites showed the best agreement as random errors are significantly lower, but overall agreement was in the 2-5 cm range with Lake Superior providing the best results and Lake Erie showing the worst. Differences appeared to due to standing water topography arising from hydrologic factors, such as the persistent westerly wind direction along the length of Lake Erie.

*G02-4-05
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Results from GOCE++ Dynamical Coastal Topography and tide gauge unification using altimetry and GOCE

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ESA has initiated the GOCE ++ study on the investigation and using ocean levelling as a novel approach to the study of height system unification across the oceans taking the recent development in geoid accuracy through GOCE data into account.
The suggested investigation involves the use of measurements and modelling to estimate Mean Dynamic Topography (MDT) of the ocean along a coastline, which contributes/requires reconciling altimetry, tide gauge and vertical land motion. Close to the coast the determination of the MDT is problematic due to i.e., the altimeter footprint, land motion or parameterization/modelling of coastal currents.
The objective of this activity is to perform a consolidated and improved understanding and modelling of coastal processes and physics responsible for sea level changes on various temporal/spatial scales. The study runs from October 2015 to march 2017 and involves the following elements
Develop an approach to estimate a consistent DT at tide gauges, coastal areas, and open ocean; Validate the approach in well-surveyed areas where DT can be determined at tide gauges; Determine a consistent MDT using GOCE with consistent error covariance fields; improving altimetry (SAR) along the coast for MSS/MDT improvement and finally connecting the global set of tide gauges and investigate trends

*G02-4-06
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

A new OGMOC mean dynamic topography model – DTU17MDT.

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Within the ESA supported Optimal Geoid for Modelling Ocean Circulation (OGMOC) project a new geoid model have been derived. It is based on the GOCO05C setup though the newer DTU15GRA altimetric surface gravity has been used in the combination. Subsequently the model has been augmented using the EIGEN-6C4 coefficients to d/o 2160.
The new DTU17MDT has been derived using this new geoid model and the DTU15MSS mean sea surface. Compared to other geoid models the new OGMOC geoid model has been optimized to avoid striations and orange skin like features. Finally, the filtering was re-evaluated by adjusting the quasi-gaussian filter width to optimize the fit to drifter velocities. Subsequently, the drifter velocities were integrated to enhance the resolution of the MDT. The results show that the new MDT improves the resolution of the details of the ocean circulation.

*G02-5-01
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

The GEOMED2 project: Geoid estimation in the Mediterranean Area

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The GEOMED2 project has been set up in order to compute an updated estimate of the geoid in the Mediterranean area. In this work, the geoid computation based on gravity data collected in the area 29o<lat.<48o -10o<lon.<41o, covering the entire Mediterranean basin, is presented. Outlier rejection and data homogenization have been carefully performed on the entire database. Low frequency components of the gravity field have been modelled using the more recent global geopotential models, such as EIGEN-6c4 and satellite only derived models (namely those based on the GOCE mission). Reduction for the terrain effect has been also accounted for using the SRTM Digital Terrain Model that has been complemented with bathymetric data. In computing the geoid, different methods have been considered. Collocation, Fast Collocation, Stokes and Stokes/FFT have been applied and discrepancies among the different estimates have been evaluated and discussed. The obtained geoid solution will then allow estimating a refined SST, both over open-sea and coastal areas, which will be used to compute permanent and seasonal currents in the Mediterranean Sea that are relevant to many physical phenomena (e.g. climate changes).

*G02-5-02
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Geomed2: gravimetric versus combined geoid model

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Computation of the geoid of the Mediterranean Sea is challenging due to the combination of poor marine gravity data coverage and their non-homogeneous quality with gravity and geoid slopes that reach significant values with high variability. The GEOMED 2 project aims at the determination of a high-accuracy and resolution marine geoid model based on the availability of improved models for gravity, thanks to GRACE and GOCE in particular, for land topography and bathymetry, and the compilation of a cleaned-up gravity database of the Mediterranean area based on BGI and SHOM data. GEOMED 2 uses land and marine gravity data, the latest satellite-only and combined GOCE/GRACE based Global Geopotential Models and a combination of MISTRALS, EMODnet and SRTM/bathymetry terrain models in the geoid computation. Marine gravity data is not available for large parts of the Mediterranean and consequently a gravimetric geoid solution will be significantly less accurate there. Gravity inferred from altimetry data, or a mean sea surface corrected for mean dynamic topography, can be used to fill the gaps. However, ocean dynamic signal always contaminates the derived gravity or synthetic geoid, which is why a gravimetric solution is preferred.
The effect on the geoid solution of using several altimeter-based models, such as DTU10, DTU13 and DTU16 gravity and mean sea surface, a new DTU model for the Mediterranean, as well as the CNES-CLS15 mean sea surface, in weighted combinations with the gravimetric data will be evaluated and quantified. To that purpose, test models will be constructed and compared to the gravimetric geoid solution. The (localized) uncertainty due to the data gaps, and the subsequent uncertainty in the ocean mean dynamic topography and geostrophic currents, can be estimated via the results of all comparisons. The processing methodology is based on the remove-compute-restore method and the fast collocation method has been used to construct all test models.

*G02-5-03
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Overview of the FAMOS efforts to improve the Baltic Sea geoid model by new marine gravity measurements

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The Baltic Sea Hydrographic Commission (BSHC) has decided to introduce the Baltic Sea Chart Datum 2000 as new common reference system for the Baltic Sea nautical charts from 2020. The Baltic Sea Chart Datum 2000 is a geodetic height reference system that uses an equipotential surface as zero level. It is based on the definition of the European Vertical Reference System (EVRS) as well as on the European Terrestrial Reference System 89 (ETRS89). The reference epoch for the postglacial land uplift is 2000.0. On land, the Baltic Sea Chart Datum 2000 will – for the time being – primarily be realized by the national levelling height reference frames. Offshore, it will be realized by GNSS (relative to networks of permanent reference stations) and a height reference surface constructed based on a gravimetric geoid model.

One of the key tasks of activity 2 in the FAMOS (Finalizing Surveys for the Baltic Motorways of the Sea) project is to improve the gravimetric geoid model over the Baltic Sea, aiming at the above realization. It is required that the model is ready by 2020 and has a well corroborated standard uncertainty better than 5 cm. This will be reached mainly (but not only) by validating and complementing the existing gravity data, with new marine gravimetry measurements made from the FAMOS hydrographic surveying vessels. Up to 2016, eight marine gravimetry campaigns have been finalized, and new FAMOS gravity and GNSS/levelling databases have been set up. It is the intention in the project to compute many interim geoid models using different computation methods on a successively improving gravity dataset. The purpose of this contribution is to give an overview of the marine gravimetry campaigns performed, present the status of the FAMOS databases and shortly describe the computation of the first FAMOS preliminary interim geoid models.

*G02-5-04
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

The altimetry-derived marine gravity field for enhanced geodetic and geological studies around Taiwan

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There are, every year, earthquakes occurring around Taiwan, which can sometimes cause destruction and loss of life. As such, it has become increasingly important to understand surface deformations in southwestern Taiwan and the northern South China Sea. This paper investigate how satellite altimetry contributes to this understanding of neotectonic fields. Waveform data from the satellite altimetry geodetic mission Jason-1 are retracked. Together with data from the repeat mission Cryosat-2, the derived altimeter sea surface heights are used to model a regionally optimal marine gravity field around Taiwan. The methodologies and techniques traditionally used for local and regional gravity determination are investigated. The modelled gravity field over the study region is compared to the latest global marine gravity models (e.g., DTU15 and Sandwell's 2014 model), as well as the ship-track gravity measurements around Taiwan. The results show that accuracy of the recovered marine gravity ranges from ˜3 mGal to ˜7.5 mGal depending on coastal zones. The vertical gravity gradient field is also generated to detect potentially hidden geological features around Taiwan. It is shown that oceanic areas around Taiwan can benefit from this new and detailed altimetry-derived gravity field, especially in waters offshore eastern Taiwan.

*G02-5-05
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Towards a new Global marine gravity field based on SARAL/ALtiKa, Jason-1 and Cryosat-2 Geodetic Missions.

Ole Andersen , * Per Knudsen , Carsten Ludwidsen , Adil Abulaitijiang
DTU Space

A latest steps towards a new global high resolution global marine free air gravity field called DTU17 is presented in this presentation. Data from the latest generation of high-class geodeit miccions creates the basis for this new global marine gravity field. A total of 9 years grom three geodetic missions including (7 years of Cryosat-2 (369 days repeat mission) as well as one year of Jason-1 end-of-life mission and one year of SARA/AltiKa geodetic mission). Older geodetic missions (ERS-1 and GEOSAT) are now nearly retired in DTU17 and provide marginal information in a very few regions.

In the Arctic Ocean we will present results from several new developments in high resolution gravity field modelling. One is a a new dual-pass retracking of SARAL/AltiKa together with an new combined empirical/physical retracking system for Cryosat-2 that uses physical retracking of the LRM data n combination with empirical retracking of the SAR and SAR-In data.

A new medium wavelength correction based on altimetry and GOCE have been introduced to deal with problems in the older remove restore technology based on EGM2008. This is particularly important for Cryosat-2 due to its ability of provide new accurate sea surface height information for gravity field determination all the way up to 88N where no altimeters have measured before.

*G02-5-06
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Comparing marine gravity and satellite altimetry in the Mediterranean area

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The combination of altimeter data and gravity allows an effective estimation of the Mean Dynamic Topography (MDT) at sea. The MDT allows then estimating the oceanic currents, a crucial information in hydrological analysis and oceanographic studies. This is of particular interest in closed seas, such as the Mediterranean Sea, due to the impact that marine physical phenomena can have in such a heavily populated area. In this work, detailed computations are carried out for comparing marine gravity data and satellite altimeter observations. Particularly, Cryosat-2 data are compared with marine gravity data in the Mediterranean area. This is done by collocation in the framework of the remove-compute-restore procedure. Different data reduction procedures based on different Global Geopotential Models and bathymetric models have been carried out in order to evaluate their impact on the final MDT and current estimates. The results have been discussed also in the framework of the Geomed2 project in view of the estimation of a refined and updated MDT surface in the entire Mediterranean basin.

*G02-6-01
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Establishing an IHRS reference station

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The definition of an International Height Reference System (IHRS) and its realization to an International Height Reference Frame (IHRF) is gaining increased importance given the outstanding results offered by the GOCE mission. Additionally, the availability of satellite altimetry data close to the coastline from the Cryosat2 SAR and SARin modes, allow the collocated determination with shipborne gravity of marine gravity anomalies not only for purely marine areas but close to the sea-land boundary as well. Finally, the existence of GOCE-derived Global Geopotential Models (GGMs), historic and current land gravity measurements, GNSS-derived ellipsoidal heights at Continuously Operating Reference Stations (CORS), and first-order levelling data set the field for the proper determination of the Earth's potential on benchmarks (BMs) that will serve as IHRF reference network stations.
The main scope of the current work is to present the theoretical aspects and practical results of determining the Earth's potential Wi at a GNSS reference station that belongs to the EUREF network. To that respect, all available gravity observations within a distance of 210 km around the AUT1 CORS reference station are collected and combined through a remove-compute-restore procedure to determine the residual disturbing potential of that specific BM. The long wavelengths are represented by the GOCE/GRACE GGM GOCO05s/GOCO05c, band-limited to d/o 250, and the high-frequencies by the SRTM 3 arcsec DTM. Least squares collocation (LSC) is used as an optimal predictor while error propagation utilizes the GGM commission error, DTM errors and the a-priori variances of the gravity data. Various configurations of the spatial distribution of the input gravity data are investigated and their influence on the final Wi prediction is outlined. Finally, conclusions on the most rigorous local/satellite/terrain data configuration are drawn along with proposals for the needed improvements and requirements.

*G02-6-02
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

The permanent tide and the International Height Reference System IHRS

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The IAG in its resolution No. 1 at the 26th General Assembly of the IUGG in Prague in 2015 adopted the mean-tide system for the International Height Reference System (IHRS). This was a partial reversal of earlier recommendations: IAG resolutions 9 and 16 at the XVIII General Assembly of the IUGG in Hamburg in 1983 had recommended the zero-tide system for handling the permanent tide in geodetic quantities.
In practice, the treatment of the permanent tide has been highly variable even after 1983. So is there anything new in the IHRS from this viewpoint? After all, we are well accustomed to mean-tide height systems at the national level. The reductions that are needed when we combine them with say 3-D positions in a conventional tide-free system and gravimetric geoid heights in the zero-tide system are also well-established.
However, there is a tidal novelty in the IHRS and that is its reference level. The national mean-tide height systems depended on a physically defined reference, usually traceable to the mean sea level at some tide gauge(s). The reference level of the IHRS is an equipotential surface where the geopotential has the conventional value W0=62636853.4 m^2/s^2. This value was first determined empirically to well approximate the global mean sea level and then adopted as a convention.
In which way does the W0 depend on the tidal system used, first in the determination, and then in the applications after the adoption as a convention? Or is there any dependence at all? This is the main subject of the presentation. I also provide a summary of reduction formulas between different tidal systems, consistent with the current IERS Conventions, and a compendium of older approximate formulas used in legacy geodetic systems.

*G02-6-03
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

On the practical realization of the fixed GBVP approach for a unification of height systems in Central Europe

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By using tide gauge observations, national height reference systems have conventionally been linked to the local mean sea level. Due to variations in the sea surface topography, different tide gauges do not realize the same height reference level in terms of a global equipotential surface. The resulting discrepancies cause height datum offsets with a magnitude of about +- 1-2m at a global scale.

To achieve a height system unification of high precision, an approach based on the solution of the fixed Geodetic Boundary Value Problem (GBVP) is proposed. On the basis of gravity disturbances and their rigorous transformation into gravity anomalies, Hotine's integral formula is solved at GNSS/leveling benchmarks in different height datum zones, which allows to estimate datum offsets as unknown parameters in a least squares adjustment.

Based on the analysis of several case studies, this contribution presents first results of a practical realization of the fixed GBVP approach for a unification of height systems in Central Europe. To this end, several practical aspects have to be considered and taken into account. Due to the limited availability of gravity data of the necessary resolution and accuracy, it is not possible to evaluate Hotine's integral formula to its global extent. Therefore, the integration area is restricted to a near zone around the respective GNSS/leveling benchmarks, where regional high-resolution gravity anomaly data is available. In order to accelerate the convergence rate of the resulting truncation error, a suitable modification of the Hotine-kernel is applied. Furthermore, to reduce systematic errors, the terrestrial gravity data is combined with the information of a satellite-based global geopotential model as well as topographic effects within a remove-compute-restore procedure.

In order to evaluate the obtained height datum offsets, results are compared to the transformation parameters of the unified European Vertical Reference Frame EVRF2007.

*G02-6-04
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Height datum unification by patching local geoid models

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National geoid models are frequently used in engineering applications to transform GNSS derived ellipsoidal heights into orthometric heights. The establishment of a unique International Height Reference System (IHRS) among neighboring countries requires the verification of the consistency between national geoids. The choice of different reference tide gauges, reference frames and ellipsoids causes biases and in general systematic effects making local geoid models inconsistent to each other. These effects can be estimated and removed by exploiting modern satellite-only models.
In the present work, a unification strategy is presented, firstly estimating biases and systematic effects by a least-squares adjustment of the local geoid residuals with respect to a satellite-only model, and then correcting the remaining geoid distortions along the national borders by collocation. The advantage is that the resulting unified geoid includes both the low frequencies of the satellite-only global model and the high frequencies of the local ones. These high frequencies are expected to be more accurate in the definition of the equipotential than those coming from a "terrestrial" global geopotential model combined with the residual terrain effect. Moreover, this procedure allows for a fast update of the unified model when a new geoid is available.
The local models to be used as test data come from the archive of the International Service for the Geoid (ISG) and the result is compared with existing global and continental geoid models. It is expected that, if the used gravity data were not preliminarily reduced by biases, these models are more affected by distortions due to the different national reference systems.
This study is performed in the frame of the Joint Working Group 2.2.1 "Integration and validation of local geoid estimates" of IAG Commission 2 . The output will represent a new product of ISG and aims to be a contribution in the frame of GGOS for the establishment of an IHRS.

*G02-6-05
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

NGS' Gravity for the Redefinition of the American Vertical Datum Project Update and Developments

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NOAA's National Geodetic Survey (NGS) defines latitude, longitude, and heights for the nation. NGS has recognized the need to update both our geometric and geopotential reference frames and plans to release updated frames in 2022. Our current vertical datum, the North American Vertical Datum of 1988 (NAVD 88), is a height system based upon geodetic leveling and realized at more than 500,000 monuments. NGS has chosen to replace this datum with one based upon a gravimetric geoid. The goal is to allow the user community to determine orthometric heights accurate to 2 cm through GNSS measurement plus a geoid height model. To create a geoid accurate to the needed 1 cm, the gravity field must be recovered at sufficient accuracy across the entire nation and its territories. NGS designed the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project to accomplish this purpose. GRAV-D involves a nationwide airborne gravity campaign designed to capture medium wavelength gravity data (20 – 500 km) to allow proper spectral blending with long-wavelength satellite gravity data from the GRACE and GOCE satellites with short-wavelength gravity information from terrestrial and shipborne measurements. From this blended gravity field we will create the gravimetric geoid that will be the basis of the new geopotential datum. This project has been underway for almost 9 years and is nearly 59% done as of February.

The GRAV-D project also includes long-term monitoring of geoid change over time so that the vertical datum will change as the Earth changes. NGS will monitor how gravity and hence the geoid changes over time and will update the vertical datum accordingly. We have named this effort the Geoid Monitoring Service (GeMS) and the research plan is currently under development.

In this presentation, we will present updates on the status of the GRAV-D project, discuss results of proof-of-concept experiments, and plans for the Geoid Monitoring Service.

*G02-6-06
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

SAR and SARIN contribution to Height System Unification in Greece

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One of the most important research topics in physical geodesy nowadays, is height system unification (HSU), at both national and global levels. The innovative Cryosat-2 satellite mission and mainly the SAR and SARin drifting modes, offer dense cross-track spacing, which contributes to the improvement of spatial resolution in both open sea and coastal zones. Taking advantage of the above, this work focuses on the prediction of Sea Level Anomalies (SLAs) and Sea Surface Heights (SSHs), close to the coastline and specifically on tide gauges/GNSS benchmarks at the land/sea boundaries. The Greek region was chosen as the study area, as its complex structure with many isles and islands constitutes an interesting area of research for the evaluation of SAR and SARin data close to coastline. Furthermore, SAR and SARin data for this region are available from the mission start (April 2010) to the end of 2016. Two different cases are investigated in this work. First, the prediction at the TG BMs is achieved via interpolation on a grid and smoothing algorithms using the total set of SAR and SARin data. Then, only the along-track data close to each point of interest are used and contribute to the prediction using simple polynomial models (first to second order), splines and Least Squares Collocation. Different prediction cases are investigated based on the general structure of the prediction area, the distribution of points which act as input data and the corresponding accuracy of the SAR and SARin SLAs and SSHs. Finally, interpolation and prediction is carried out to 'bridge' the data between SAR-SARin and LRM-SAR modes using novel algorithms, as well as to detect the existence of possible biases during the alternation of the mask mode.

*G02-P-02
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

What is the real meaning of the Secondary Indirect Effect?

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Researchers who are faced with the task of transforming the free-air gravity anomalies from real space to the Helmert or the NT space would have met with a term called Secondary Indirect Topographical Effect, SITE for brief. Here the spaces are defined by their distribution of topographical mass density and they share the normal gravity field as well as the coordinate systems used for describing the processes that take place in these spaces. The Helmert space is defined by the two-dimensional distribution of a condensed topographical mass layer on the geoid in terms of Helmert's second method of condensation. Another space is the NT space in which the entire topographical mass is removed, i.e. it has a zero topographical density distribution. The SITE is one term in the sequence of terms applied to a gravity anomaly in the “from space", say the real space, to obtain gravity anomaly in the “into space", say, the Helmert space. The origin of all the terms in the sequence can be intuitively understood, except for the SITE, which is also missing in the transformation equations/sequences for other gravity related quantities.

On the other hand, people who deal with these different spaces, speak of the direct transformation from the “from space" to the “into space" and the inverse transformation from the “into space" to the “from space". The direct transformation is associated with the “direct effects" while the inverse transformation is associated with the “indirect effects". So, is the SITE associated with the inverse transformation? It turns out that it is not. Instead, the SITE must be understood as transforming from one space to another the rule of computing gravity anomalies. This means transforming the rule of identifying the “corresponding" equipotential surfaces in the real gravity field and the normal gravity field. This study explains the physical meaning and formulates mathematical transformations of the SITEs between the Helmert and NT spaces.

*G02-P-03
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Regional geoid computation by Least Squares Modified Hotine's formula with Additive Corrections

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Geoid and quasigeoid modelling from gravity anomalies by the method of Least Squares Modification of Stokes' formula with Additive Corrections (LSMSA) is adapted for the usage with gravity disturbances and Hotine's formula. The biased, unbiased and optimum versions of least squares modification are considered. Equations are presented for the four additive corrections that account for the combined (direct plus indirect) effect of downward continuation (DWC), topographic, atmospheric or ellipsoidal corrections in geoid or quasigeoid modelling. The geoid or quasigeoid modelling scheme by the least squares modified Hotine formula is numerically verified, analysed and compared to the Stokes counterpart in a heterogeneous study area.

Both, the approximate geoid models (before the combined corrections) and the additive corrections computed for use with Stokes' or Hotine's formula differ most in areas of high elevation. Over the study area with elevations up to 2 km, the approximate geoid models differ by 7 mm on average with a 3 mm standard deviation (STD) and a maximum of 1.3 cm. The additive corrections, out of which only the DWC correction differs significantly, improve the agreement between respective geoid or quasigeoid models to an average difference of 5 mm with a 1 mm STD and a maximum of 8 mm.

*G02-P-04
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Establishment of the new Japan Gravity Standardization Network(JGSN) 2016

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Geospatial Information Authority of Japan (GSI) has released a new JGSN2016 in March 2017 for the first time in 40 years using the latest land gravity data over Japan measured by highly accurate gravimeters. Before that, JGSN75, which is established by GSI in 1976, has been used as a gravity standard in Japan. It is the gravity network decided by only relative gravity measurements based on IGSN71 and has been widely utilized in both social and scientific fields such as determining domestic altitude standards, correcting the results of leveling surveys, exploring underground structures reflected hidden active faults and calibration of measuring instruments. On the other hand, due to mainly active crustal movements, the gravity values vary both spatially and temporally in Japan according to the redistribution of the underground mass. In fact, the difference between the gravity value of JGSN75 and current one reached 0.1mGal at maximum. In addition, along with the recent advancement of gravity measuring instruments and technologies, more accurate gravity standard had been required.
JGSN2016 was conducted by both absolute and relative gravity data carried out by GSI between 2002 and 2016, including gravitational changes accompanying big earthquakes such as 2011 Tohoku earthquake. Especially, in order to obtain absolute gravity values which are consistent with international standards, we calibrated our FG5 absolute gravimeter once a year to the one owned by National Institute of Advanced Industrial Science and Technology (AIST)which participated in the international comparative observation supported by BIPM so that we could. Furthermore, we
established 33 absolute gravity points with precise position coordinates and reviewed and unified analysis parameters such as tidal correction as new attempts. With this kind of ingenuity, we realize a highly accurate and reliable gravity network covering all over Japan.

*G02-P-05
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Local hydrological disturbances on gravity revealed by simultaneous observation with a gPhone and a superconducting gravimeter

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In August 2016, continuous gravity observation with a gPhone gravimeter (# 133) was started at the F-net IGK (Ishigaki) station of the National Research Institute for Earth Science and Disaster Resilience (NIED), in order to supplement the superconducting gravimeter CT36 at the VERA Ishigakijima station of the National Astronomical Observatory of Japan. The F-net station is about 900 meters away from the VERA station. In spite of some initial problems, the gPhone gravimeter has been producing high-quality records since late November, 2016, thanks to the stable condition inside the observation vault free from the effects of solar radiation and ambient temperature changes. From the comparison of two month long data, it is shown that the gravity records from the two gravimeters are in agreement to within 5 microgals. The small difference in the observed gravity is highly likely to reflect the different responses of gravity to local precipitation at the two sites. Detailed investigation of this signal in comparison with meteorological data will be useful for precise modeling and correction of hydrological disturbances on gravity, and then retrieving deep underground signals (i.e. slow slip events).

Combined use of a superconducting gravimeter and Scintrex gravimeters for hydrological correction of precise gravity measurements - A superhybrid gravimetry

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Precise gravity observations are often subject to influence of temporally variable distribution of underground water near the observation sites. It is in general difficult to model and correct such effects from the observed gravity series, because it requires knowledge of the hydrological nature of the underground which varies from place to place. The superconducting gravimeter CT36 at Ishigakijima, Okinawa, Japan also experiences very complicated effects of underground water, apparently combined with the atmosphere and the ocean. Effects of the fluids near the surface on gravity must be precisely corrected so that the possible gravity signals associated with the long-term slow slip events occurring near the Ryukyu trench can be detected.
To overcome this difficulty, we employ combined use of the superconducting gravimeter (SG) and Scintrex CG-5 gravimeters. The latter are used as mobile instruments, measuring relative gravity values with respect to the SG pier as in a local gravity survey. One of the advantages of the CG-5 gravimeter is that it enables continuous measurements and therefore comparison with the SG, thus greatly mitigating the problems of instrumental drift inherent to mobile gravimeters. Under the assumption that temporal gravity changes are common within the survey area, using the SG data as reference helps improving estimates of the local gravity field significantly.
We made an experiment of this kind of measurements (which we term superhybrid gravity measurements) using two CG-5's at Ishigakijima in January 2017. Preliminary analysis of the data has shown that relative gravity values at a particular point measured on different days were in agreement at 1 microgal precision. We will present further results and discuss temporal changes of gravity in relation to the dynamics of underground water.

*G02-P-07
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Application of Local Functions in Airborne Gravimetry for Regional Geoid Improvement

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Local functions such as the Radial Basis Functions (RBF) have been extensively studied and applied in physical geodesy in the recent decade, such as in Schmidt et al (2007) and Klees et al (2008), and in many other studies that focused mainly on satellite mission related applications. Considering that airborne gravity data is usually limited in both the space domain and the frequency domain, it is a perfect match to the characteristics of the RBF. Thus, it is a natural choice to process and model the airborne gravity data with RBF, though in the literature for airborne gravimetry various other methods such as Least Squares Collocation and the inverse of Abel-Poisson's integral (the Fredholm integral equation of the first kind) are often used to take advantage of the airborne data for local geoid improvement. In this study, first, a series of simulation tests are carried out to demonstrate the reliability and versatility of using RBF to model and to downward continue the airborne data, as well as to detect outliers and systematic bias in problematic flight lines typically find in an airborne campaign. Then the final verified (in term of closed loop simulation tests) algorithm is applied to the real airborne flight data in the area of Puerto Rico and US Virgin Islands for local gravity field modeling.

*G02-P-09
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Topographic correction and covariance function modelling over the coastal regions

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Using the conventional remove-compute-restore (only removing the Global Geopotential Models) technique, the theoretical assumption of homogeneity and isotropy in the Least Square Collocation (LSC) algorithm is not always satisfied in the coastal regions and mountainous regions. High resolution bathymetry data (e.g., SRTM30, spatial resolution of around 1 Km) is used to account for the strong correlation in the short wavelength (1~10 km) gravity features with topography and bathymetry. Hence, the Topographic Correction (TC) is a critical step in the reduction of the gravity functionals (e.g., height anomaly and gravity anomaly), to comply with the theoretical assumption of LSC.
DTU has been working on the improved coastal marine gravity from satellite altimetry (mainly CryoSat-2). Previous studies show that the terrain correction using Residual Terrain Model (RTM) w.r.t. residual gravity anomalies are slightly different w.r.t the residual height anomalies over the shallow regions close to the coast (or regions including islands). This should be well examined when the (sea level) height anomalies are to be reduced by TC and further the marine gravity field is derived using LSC. In this work, the TC computation (both w.r.t. the height anomalies and gravity) will be conducted in several regions (patches) around Mediterranean, Chile, islands of Indonesia where the true gravity data is available for validation. Both the spatial integration and FFT approach will be tested due to the steep topographic changes in the selected regions. The reduction performance is then evaluated through proper covariance function modelling and analysis before the LSC.

*G02-P-10
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Geoid and Moho-depth modeling in Cyprus

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A high-resolution gravimetric geoid determination was carried out for the wider area of Cyprus using gravity data from national and international databases, local and global digital elevation and bathymetry models and satellite altimetry data for the surrounding sea areas. The EGM08 global geopotential model was used as a reference surface to model long to medium frequencies of the gravity field spectrum. Terrain and bathymetry effects on gravity anomalies have been studied through different reduction schemes and various validation procedures were applied in order to finally produce a reliable gravity grid of 1 arcmin resolution. Geoid solutions were computed by Least Squares Collocation (LSC) and Stokes integral employing Fast Fourier Transform (FFT) techniques using the rigorous 1D spherical kernel, within a Remove-Compute-Restore (RCR) approach. The geoid solutions show an absolute accuracy at the level of 4cm for the continental area of Cyprus, after comparison with GPS/leveling derived geoid heights, and a relative accuracy at the level of about 8ppm over baselines of 10km. These accuracies meet the nowadays requirements of a wide spectrum of geodetic, geophysical and engineering projects. In a second step, Moho depths were estimated for both land and marine areas following the inversion of the previously compiled gravity grid complemented with density and GOCE data. The geoid and Moho models computed in this study show the strong signature and peculiar futures of the gravity field in the test area and the wider eastern Mediterranean basin. To this respect, further geodetic and geophysical considerations form the basis for future important research in the area under study.

*G02-P-11
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Preliminary Results of Mass Redistribution from Repeated Campaigns of Precision Gravimetry in the Wandan Mud Volcano, Taiwan

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The Wandan mud volcano, classified as an intermittent one, is located in the coastal plan of Kaohsiung and Pingtung, SW Taiwan. Although its past eruptions are not regular, it has erupted at least once a year, except for 1999, since 1988. Despite the exceptional consistency of eruptions, the amount and period of eruptions and the mass redistribution underneath the area have been little known by far. In this study, we conducted repeated campaigns of precision gravimetry to monitor the temporal gravity change once a few months since 2015 with Microg LaCoste FG5 absolute gravimeter and Scintrex CG-5 relative gravimeter. We arranged the before and after gravity measurements for eruptions. Preliminary result reveals that there's a 30 μGal absolute gravity increase near the crater before an eruption on April 28, 2016 and a 150 μGal drop after that. The spatial feature of the absolute gravity increases in the western area and decreases in the southern part. The result confirms that the temporal gravity change and possibly the mass redistribution caused by the Wandan mud volcano is sensible to the precision gravimetry. Though some difficulties such as hydrology and other corrections need to be overcome, the promising result is anticipated to be helpful to the understanding of the activities of the Wandan mud volcano and diapirs in the area.

*G02-P-12
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Determination of Moho depth models for Greece using different gravity inversion methods

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In this study, three of the most common methods of determining the Mohorovicic (Moho) discontinuity are employed towards the development of new Moho-models for the area of Greece by gravity inversion. The first method is conducted in the spectral domain and is based on an iterative approach following the Parker-Oldenburg formula and applying a low-pass filter for the stabilization of the finally produced solution. The background of the second method is in line with the well-known Bott's method combined with a Gauss-Newton formulation and a regularization technique focusing on a well-controlled solution. The entire procedure incorporates tesseroids in the modelling part and an adaptive iterative scheme for the optimal approximation of the finally determined Moho-depth surface. The solution of Vening-Meinesz and Moritz inverse isostatic problem is carried out by the third method along with non-isostatic corrections applied to the Moho-height differences estimated by the gravity data and the seismic constrained information incorporated in the inversion algorithm. The gravity data used in the computations of the three methods were derived from GOCO05s and EGM08 global geopotential models. The aforementioned methods are reviewed in terms of their computational efficiency as well as the assumptions and limitations required for their numerical evaluation. The Moho models derived by the three methods are inter-compared and compared also with a model derived for the test area by a previous study, which is based on high resolution local gravity databases. An external validation test of the new models was performed by comparing with Moho depths derived by seismic data in a number of stations in the area under consideration. Some remarks, conclusions and suggestions are finally drawn mainly related to the performance of each method and taking into account the strong features of the gravity field in the area under study.

*G02-P-13
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Towards the best GOCE gravity gradients

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The GOCE gravity gradients show perturbations that correlate with the geomagnetic field. In particular the cross-track gravity gradient is significantly perturbed in the regions around the geomagnetic poles. Recently, it was found that the perturbing effect is due to an unmodelled quadratic factor that occurs in the conversion from the electrode control voltages to accelerations, which caused the highly dynamic acceleration signal from cross-track drag to map onto the cross-track gravity gradient. Fortunately, it is possible to model and completely remove the perturbing effect, arriving at a more accurate, “clean" cross-track gravity gradient, which is demonstrated in this presentation.
Also the other gravity gradients show perturbations that correlate with the magnetic field. Those perturbations are much smaller than the perturbation of the cross-track gravity gradient, but appear systematic and are therefore important to remove as well. We will show in this presentation to which extent these perturbation can be removed from the gravity gradients by re-calibrating the accelerometer data and assess the impact on the gravity field retrieval from GOCE data.

*G02-P-15
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Evaluation of the gravity and altimetry data in the Baltic Sea region and computation of the new quasi-geoid model for the territory of Poland

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The gravimetric quasi-geoid models in Poland were computed using FFT, collocation and KTH methods. In all cases the same gravity data from the southern part of the Baltic Sea, geopotential model EGM2008, and the same digital terrain model, were used. The accuracy of the computed models was estimated using GPS/levelling data from the POLREF network.
Marine gravity anomalies used in the quasi-geoid model computations cover the very limited southern part of the Baltic Sea. The currently available gravity data from the satellite altimetry, e.g. the DNSC08GRA global marine gravity field, are covering the whole Baltic Sea. The usage of this data source should improve the quality of existing quasi-geoid models.
The first aim of the work is the comparison and validation of gravity anomalies from the DNSC08GRA model and the shipborne gravity anomalies along the Polish coast and in the Gulf of Bothnia. The next step, is the computation of new gravimetric quasi-geoid model for the territory of Poland, using gravity data from the satellite altimetry, the EIGEN-6C4 and GECO geopotential models, and the chosen DTM. The accuracy of the computed new model is estimated using the high precision ASG-EUPOS network connected to the new vertical datum PL-EVRF2007-NH.

*G02-P-16
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

PCA and along track filtering of Crysoat2 SSH for DOT modeling in the Mediterranean

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With the availability of an abundance of earth observation data from satellite altimetry missions, monitoring of the sea level variations is gaining increased importance. Given the availability of altimetric sea surface heights (SSHs) one can employ all such available data to estimate the mean dynamic ocean topography (DOT) as well as its time varying, part. ESA's Cryosat2 mission with its orbit characteristics, measurements mode and accuracy can be used for sea level anomaly (SLA), geoid and DOT modeling over the entire Mediterranean basin. The main goal of this work is to use the altimetry data of Cryosat2 from the mission start until the end of 2016 for the determination of the DOT for the Mediterranean Sea. To this respect, along-track filtering of the Cryosat2 SLAs, derived from the combination of the original SSHs with the GOCO05c GOCE-based Global Geopotential Model (GGM) is investigated, while through a Principal Component Analysis the structure of the data variability will be explored. Principal Component Analysis (PCA) is used to investigate the temporal spatial variations of DOT and derive annual and secular trends. For the along-track filtering, spectral filters will be examined, based on various options of FIR and IIR filters. Filtering is applied along the whole passes of the satellite in order to remove/reduce the effects of geoid omission and commission errors still remaining in the DOT due to the limited representation offered by the GGM. Finally, for the evaluation of the new filtered DOT models, the RIO_MED and SMDT synthetic models for the Mediterranean and DTU10 have been used.

*G02-P-17
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

The GEOMED2 project: Multi-resolution aspects and aliasing in topographic effects for geoid and gravity determination

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One of the key aspects of the GEOMED2 project is the determination of a high-accuracy and high-resolution geoid model for the Mediterranean Sea along with the generation of gravity grids for various types of gravity anomalies like free-air, complete Bouguer, isostatic, etc. A crucial point in both geoid determination and gravity reductions, using the remove-compute-restore method, is the proper modelling of the topography/bathymetry effects on the available gravity anomalies. When estimating the high-frequency content of the gravity field spectrum the robustness and rigorousness of the determined topographic effects relies on both proper theoretical treatment and the soundness of the Digital Terrain and Bathymetry Model (DTM/DBM) used. Over land areas, the latest SRTM-based DTMs offer high-accuracy and high-resolution information on the topographic variations, in the sense that they properly manage to model the high-frequency contributions of the topographic masses. Over marine regions the situation is quite different, since the resolution of the DBMs available is not capable to remove the high-frequencies present in shipborne marine gravity data. Moreover, marine gravity data themselves do not have in many cases the necessary spatial resolution to rigorously model the high-frequencies depicted in the DBM. The main focus of the present work is on treating the aforementioned problems, i.e., to investigate and properly determine topographic effects over both land and marine areas to efficiently reduce land and marine gravity data towards geoid determination. Additionally, aliasing effects on the estimated topographic effects are investigated and the corresponding errors introduced in gravity anomalies and geoid heights are determined. Then, the DTM/DBM combination that provides the overall best results, in terms of the smoothness of the residual gravity anomalies, is outlined along with the final topographically corrected gravity anomalies and geoid indirect effects.

*G02-P-18
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

The GEOMED2 project: Geoid and circulation in the Mediterranean Sea

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The main scope of the GEOMED2 project is the determination of a high-accuracy and high-resolution geoid model for the Mediterranean Sea using land and marine gravity data and the more recent Global Geopotential Models, those based on GOCE/GRACE data. The processing methodology is based on the well-known remove-compute-restore procedure and both stochastic and integral/spectral methods for the determination of the geoid and the rigorous combination of heterogeneous data. All the available gravity observations for the wider Mediterranean basin were collected, validated, homogenized and unified in terms of their horizontal coordinates and gravity systems, so as to derive a reliable gravity data base to be used for the determination of the geoid. The so-determined geoid model can form the basis for height-system unification in the Mediterranean area. Also, by comparison with altimeter data, this geoid can be used to derive high-resolution models of the Mean Dynamic Topography that will allow estimating the marine circulation in the Mediterranean Sea.
The final delivered products of this project will be the geoid estimate in the Mediterranean area, the Mean Dynamic Topography of the Mediterranean Sea and the implied circulation model.

*G02-P-19
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

CryoSat-2-only gravity model of the Arctic ocean: case study in Greenland Sea

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The Arctic marine gravity has not been well mapped due to weather conditions or political interests. The polar orbiting satellite altimetry mission (e.g., CryoSat-2) covers the Arctic up to latitude 88 and has the great potential of achieving the Arctic marine gravity maps from altimetry. Combined with the dense across track and improved along track resolution achieved by synthetic aperture processing, the arctic sea ice freeboard and sea level can be achieved and further transformed to the gravity anomalies using the Least Square Collocation (LSC).
In this work, we will derive the marine gravity for Greenland Sea using the remove-compute-restore technique and LSC algorithm. The data preparation is challenging due to the changing operating mask of CryoSat-2 and presenting sea ice in the footprints. A careful data editing scheme combined with sea ice flags will addressed. The existing bathymetry chart of Arctic Ocean, known as IBCAO will be introduced to further reduce the altimetric data. Earlier studies show that using the FFT method, a 4 mGal accuracy can be achieved and with 6 years of data, a better accuracy is expected.

*G02-P-20
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

Local vertical datum validation through the incorporation of GOCE variance and covariance information

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After the completion of the GOCE mission, the information on height system validation and unification has been enriched, especially in the low to medium frequency of the gravity field spectrum. GOCE information is used for estimating height and/or geopotential offsets with respect to a conventional reference geopotential value, employing available GNSS/Leveling observations on trigonometric BMs and a GOCE-based geoid model. The scope of this work is to investigate the influence of GOCE errors in the determination of the Hellenic LVD. This is facilitated through a least-squares (LS) based adjustment of collocated GNSS/Leveling and GOCE geoid heights over a network of 1542 BMs in mainland Greece. The latest TIM-R5 and GOCO05s GOCE and GOCE/GRACE global geopotential models are used to represent the contribution of GOCE and GRACE to the Earth's gravity field. Four different weighting scenarios are used including standard a-priori error for the BMs heights, the GNSS heights and the geoid undulations, cumulative errors for the geoid heights and variance/covariance information from GOCE geoid models. The local geopotential offset Wo(LVD) is also calculated utilizing the weighting scenarios. Finally, variance component estimation is performed to evaluate the height (h, H, N) variance/covariance matrices using the GPS/leveling errors from the above weighting schemes.

*G02-P-22
IAG Symposium / IAG02. Gravity field / G02. Static gravity field

International Digital Elevation Model Service (IDEMS): A Revived IAG Service

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A newly developed International Digital Elevation Model Service (IDEMS) is now available under the umbrella of the International Gravity Field Service of the International Association of Geodesy. Hosted and operated by Environmental Systems Research Institute (Esri) (http://www.esri.com/), the new IDEMS website is available at: https://idems.maps.arcgis.com/home/index.html.

IDEMS provides a focus for distribution of data and information about various digital elevation models, including spherical-harmonic models of Earth's global topography and lunar and planetary DEM. Related datasets, such as representation of inland water within DEMs, and relevant software which are available in the public domain are also provided.

Currently, IDEMS serves as repository of links to providers of global terrain and bathymetry, terrain related Earth models and datasets such as digital elevation data services managed and maintained by Esri (Terrain and TopoBathy), Bedmap2-Ice thickness and subglacial topographic model of Antarctica and Ice, Cloud, and Land Elevation ICESat/GLAS Data, as well as planetary terrain data provided by PDS Geosciences Node at Washington University, St. Louis. These services provide online access to a collection of multi-resolution and multi-source elevation and bathymetry data, including metadata and source information.

In addition to IDEMS current holdings of terrestrial and planetary DEMs, some topography related products IDEMS may include in future are: dynamic ocean topography, 3D crustal density models, Earth's dynamic topography, etc. IDEMS may also consider terrain related products such as quality assessments, global terrain corrections, global height anomaly-to-geoid height corrections and other geodesy-relevant studies and products.

IDEMS encourages contributions to the site from the geodetic community in any of the product types listed above. Please contact the authors if you would like to contribute or recommend content you think appropriate for IDEMS.

*G03-1-01
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Current Status of the GRACE Mission

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The twin satellites of the Gravity Recovery and Climate Experiment (GRACE) were launched on March 17, 2002 and have operated for over 15 years. The mission objectives are to sense the spatial and temporal variations of the Earth's mass through its effects on the gravity field at the GRACE satellite altitude. The major cause of the time varying mass is water motion and the GRACE mission has provided a continuous decade long measurement sequences which characterizes the seasonal cycle of mass transport between the oceans, land, cryosphere and atmosphere; its inter-annual variability; and the climate driven secular, or long period, mass transport signals. In 2012, a complete reanalysis of the mission data, referred to as the RL05 data release, was initiated. The monthly solutions from this effort were released in mid-2013 with the mean fields following in subsequent years. The mission is entering the final phases of operations with mission end expected to occur before July 1, 2017. The current mission operations strategy emphasizes extending the mission lifetime to minimize the break in the measurements before the GRACE Follow-On Mission is launched. This presentation will review the mission status and the projections for mission lifetime, describe the issues that influence the operations philosophy, discuss the approaches to bridge the gap between GRACE and GRACE FO and discuss the content of the science data products during this phase of the mission.

*G03-1-02
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

GRACE Follow-On: Overview and Current Mission Status

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The GRACE Follow-On Mission has now advanced to the Assembly and Test Phase with the delivery of essentially all satellite subsystems and science instruments. The two spacecraft have been transferred to Ottobrunn near Munich for several months of operational testing in the IABG test center. The project team is conducting tests of satellite and instrument operation and performance and putting together updated simulations of expected performance on-orbit, including intersatellite ranging (both microwave and laser), accelerometer, thermal variability and deformation, and other errors. In addition, all required ground analysis software of the Science Data System is in development and testing at JPL, UTCSR, and GFZ, in preparation for fully integrated end-to-end (international) testing from Level-1 through Level-3 data within 2017. Recently, the GRACE Follow-On launch was confirmed in a rideshare agreement between GFZ and Iridium Satellite LLC. GRACE Follow-On is expected to launch in the period from December 2017 to February 2018, together with 5 Iridium-Next satellites, on a Space-X Falcon-9 from Vandenberg Air Force Base in California.
In this presentation, we will provide the detailed status of project integration and test, the latest results of expected science performance, and schedule for remaining project milestones before and after launch.

*G03-1-03
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Towards deriving temporal sampling requirements for future satellite gravimetry missions

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Studies have shown that future satellite gravimetry missions utilizing low-low satellite-to-satellite tracking (LL-SST) that have an improved onboard measurement system relative to the Gravity Recovery and Climate Experiment (GRACE) will be limited by temporal aliasing errors. The improved measurement system comes primarily in the form of improved electrostatic accelerometers to measure nonconservative forces as well as a laser interferometer to measure changes in distance between the satellites. Temporal aliasing errors are accumulated primarily because of deficiencies in models of high frequency mass variations (ocean tides, atmosphere and ocean mass variations), which are required in the first place because of the limited temporal sampling of a single pair of satellites. It has been shown that the impact of temporal aliasing errors on the gravity retrieval can be reduced substantially by implementing a mission architecture consisting of two pairs of satellites; however, even in this case the temporal aliasing errors remain as the dominant source of error. In this study, we make a first attempt to define temporal sampling requirements for future satellite gravimetry missions to go beyond the performance that two pairs of satellites can offer. We probe both the spatial and temporal characteristics of temporal aliasing errors to understand their impact on the gravity retrieval using numerical simulations. Through such studies, we can hypothesize as to what spatial and temporal scales of gravity field variations must be directly observed to gain specified improvements in accuracy and spatio-temporal resolution with which mass flux in the Earth system can be resolved.

*G03-1-04
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Constellations of Next Generation Gravity Missions: mapping and mitigation of ocean tide model errors

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The GRACE and GOCE satellite missions have shown the great potential of using space-borne gravimetry for observing mass transport in the system Earth. However, for meeting future user needs, it is crucial to enhance both the spatial and temporal resolution. This can be achieved by a Bender-type Next Generation Gravity Mission (NGGM) that consists of a constellation of two GRACE-type satellite tandems, with one pair flying in a (near-)polar orbit and the other in an inclined orbit. In addition, GRACE-type satellites will be implemented with improved sensor packages, including laser-based low-low satellite-to-satellite tracking (ll-SST) instruments, more precise accelerometers and state-of-the-art star trackers.

The European Space Agency (ESA) study “ADDCON" (ADDitional CONstellations) aims at investigating the impact of several orbit design choices on the performance of temporal gravity field retrieval by Bender-type NGGMs. Simulation studies have indicated that for such constellations aliasing of errors in ocean tide models is a dominant error source in retrieved temporal gravity field. As part of the ADDCON study, ocean tide model errors are mapped first in terms of ll-SST range-rate residuals for several Bender-type NGGMs, with orbits varying in altitude, repeat period and inclination (prograde and retrograde). This provides among others insight in the geographical distribution of ll-SST observation residuals due to errors in ocean tide models. Second, the ocean tide model errors are mapped to gravity field errors in terms of spherical harmonic (SH) expansions for retrievals ranging from one day to a month and for maximum SH degrees ranging from 10 to 120. Third and finally, the possibility of mitigating the impact of ocean tide model error on gravity field retrieval by tuning the set of estimated parameters has been explored (including estimation of empirical accelerations, so-called Wiese approach, etc.).

*G03-1-05
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Status of development on the future accelerometers for next generation gravity missions

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The GRACE FO mission, led by the JPL and GFZ, is an Earth-orbiting gravity mission, continuation of the GRACE mission, which will produce an accurate model of the Earth's gravity field variation providing global climatic data during five years at least. Europe and US propose new gravity missions beyond GRACE-FO, with performance improved thanks to laser interferometry and better accelerometers. ONERA has procured the accelerometers for the previous geodesic mission (CHAMP, GRACE, GOCE and now GRACE-FO) and continue to improve the instruments to answer to the challenge of the future missions according to two main axes:

Firstly, a new design of electrostatic accelerometer is proposed, based on MicroSTAR configuration, a 3-axes ultra-sensitive accelerometer, with a cubic proof-mass. This new design gives, beyond the linear acceleration, the 3 angular accelerations for a better satellite attitude control. For linear acceleration, the performance is improved by at least an order of magnitude with respect to GRACE-FO.

Secondly, ONERA studies the hybridization of such electrostatic accelerometer with cold atom interferometer technology. Each of these two types of instruments presents their own advantages which are, for the electrostatic sensors, their demonstrated short term sensitivity and their high TRL, and for atom interferometer, the absolute nature of the measurement and therefore no need for calibration processes. These two technologies are very complementary and a hybrid sensor could be the opportunity to make a big step in this context of gravity space missions. We present here the first experimental association on ground of an electrostatic accelerometer and an atomic accelerometer and underline the interest of calibrating the electrostatic sensor with the atomic interferometer.

*G03-2-02
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Time variable gravity from kinematic orbits of LEO satellites – A 15+ years series of monthly solutions without gaps

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Gravity field recovery from high-low satellite to satellite tracking has been applied successfully to former gravity missions like CHAMP and GOCE. The process to derive gravity field estimates from GNSS observations is separated into two steps. First kinematic orbits for the LEO satellite are derived from the GNSS measurements. Subsequently the kinematic orbit positions are introduced as pseudo-observations estimate the gravity field. We make use of a precise point positioning approach based on raw GNSS observations to retrieve kinematic orbits with accuracies of a few centimeters. Some special aspects of the approach are: antenna center variations for phase and code observations, azimuth and nadir angle dependent antenna center variations for transmitters, and azimuth and nadir angle dependent accuracy information for each observation type. In this contribution we will show the impact of these specific processing aspects on the orbit quality and on derived gravity field estimates. The method has been applied to a number of LEO missions, including non-gravity missions like Swarm, Terra-SAR-X, TanDEM-X, MetOp, or Jason 1&2. Based on kinematic orbits from more than 10 satellite missions a time series of individual and unconstrained monthly gravity field solutions has been produced. The series starts in January 2002 and spans more than 15 years without gaps. We demonstrate that it is possible to observe mass variations for regions like Greenland, the Antarctic, the Amazon basin, and other large river basins, down to areas as small as the Caspian Sea.

*G03-2-03
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Near real-time gravity and its applications in the era of Next Generation Gravity Missions - Insights on the ESA-ADDCON project

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Next Generation Gravity Missions (NGGMs) expected to be launched in the mid-term future have set high anticipations for an enhanced monitoring of mass transport in the Earth system, establishing their products applicable to new scientific fields and serving societal needs. The European Space Agency (ESA) has issued several studies on concepts of NGGMs. Following this tradition, the project “Additional Constellations & Scientific Analysis Studies of the Next Generation Gravity Mission" picks up where the previous study ESA-SC4MGV left off.

One of the ESA-ADDCON project objectives is to investigate the impact of different orbit configurations and parameters on the gravity field retrieval. Given a two-pair Bender-type constellation, consisting of a polar and an inclined pair, choices for orbit design such as the altitude profile during mission lifetime, the length of retrieval period, the value of sub-cycles and the choice of a prograde over a retrograde orbit are investigated. Moreover, the problem of aliasing due to ocean tide model inaccuracies, as well as methods for mitigating their effect on gravity field solutions are investigated in the context of NGGMs.

The performed simulations make use of the gravity field processing approach where low-resolution gravity field solutions are co-parameterized in short-term periods (e.g. daily) together with the long-term solutions (e.g. 11-day solution). This method proved to be beneficial for NGGMs (ESA-SC4MGV project) since the enhanced spatio-temporal sampling enables a self-de-aliasing of high-frequency atmospheric and oceanic signals, which may now be a part of the retrieved signal. The potential added value of having such signals for the first time in near real-time is assessed within the project.

*G03-2-05
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Amplitude-phase representation of GRACE spherical harmonic spectra

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Representing the spherical harmonic spectrum of a field on the sphere in terms of its amplitude and phase is termed as its polar form. While the polar form of the Fourier spectrum, especially in time-series analysis and image processing, is well understood, it is an alien concept in geodesy. To this extent, we first show that spherical harmonic synthesis can be interpreted as a weighted (by amplitude) sum of rotated (by phase) spherical harmonics. As an example, we explore the polar forms of the monthly GRACE time-variable gravity field data before and after filtering. The impact of filtering on amplitude is well understood, but that on phase has not been studied previously. Here, we demonstrate that certain class of filters only affect the amplitude of the spherical harmonic spectrum and not the phase, but the others affect both the amplitude and phase. Further, we also demonstrate that the filtered phase helps in ascertaining the efficacy of decorrelation filters used in the GRACE community.

Using Swarm and Sentinel observations for time-variable hl-SST gravity field determination

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Equipped with geodetic-grade on-board GPS receivers and star trackers, the three satellites of the Swarm mission can be used to determine the long-wavelength part of the Earth's gravity field including its time variations by means of high-low satellite-to-satellite tracking (hl-SST). This is also true for ESA's Sentinel satellites, although their slightly higher orbital altitude degrades their sensitivity to the gravity field. Hl-SST based gravity field solutions are of special interest to fill the gap between the dedicated gravity missions GRACE and GRACE-FO.

In this contribution the latest results obtained at the Astronomical Institute of the University of Bern (AIUB) as well as at the German Research Centre for Geosciences (GFZ) are presented focusing on the following topics: (1) Systematic errors in Swarm gravity field solutions along the Earth's geomagnetic equator caused by ionospheric disturbances and their mitigation by GPS data screening and/or updated tracking loop settings of the GPS receivers. (2) Comparison of monthly AIUB and GFZ Swarm solutions that are generated with different approaches. (3) Added value of Sentinel-1A, -2A, and -3A satellites (which are not affected by the aforementioned systematic degradations) to the very low degrees of the Swarm gravity field solutions.

*G03-3-01
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Preliminary results from CSR RL06 GRACE gravity solutions

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The GRACE mission data will be reprocessed in order to be consistent with the first gravity products released by the GRACE-FO project. The improvements in the next generation GRACE Release-06 (RL06) gravity products will come from the improvements in GRACE Level-1 data products, background models and processing methodology. This paper will discuss the planned and realized improvements for CSR – RL06 gravity products and present the preliminary results. This paper will discuss the evolution of the quality of the GRACE solutions and characterize the errors, especially over the past few years. We will also discuss the possible challenges associated with connecting the GRACE time series with that from GRACE-FO.

*G03-3-02
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Combination of monthly gravity field solutions – transition from an EGSIEM prototype service into an IAG service

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One of the main objectives of the project European Gravity Service for Improved Emergency Management (EGSIEM) is to establish a prototype service to combine monthly gravity field solutions from the current GRACE and the future GRACE-FO mission in order to deliver improved gravity field solutions for applications in Earth and environmental science research. Five analysis centers are currently contributing to these prototype service activities, where combinations on the solution level and more rigorous combinations on the normal equation level are performed. We report on the current achievements and the transition from the prototype phase into regular service operation under the umbrella of IAG's International Gravity Field Service (IGFS), which will ensure continuation beyond the EGSIEM project ending after three years of funding by the end of 2017.

*G03-3-03
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

On computation of along-track potential and Line-of-Sight (LOS) acceleration difference using GRACE inter-satellite ranging data for time-variable gravity analysis

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In situ along-track potential difference and LOS acceleration difference can be computed from GRACE orbit and inter-satellite range-rate and range-acceleration data. We study the systematic errors in deriving along-track potential difference from inter-satellite range-rate and LOS acceleration difference from inter-satellite range-acceleration. Since GRACE can be considered as a long single-axis gradiometer, approximating gradiometric observable (i.e. LOS acceleration difference divided by inter-satellite range) by along-track gravitational gradient is also discussed. In all three cases (potential, gravity and gravity gradient), we formulate the errors explicitly in terms of cross-track and radial components of the inter-satellite velocity vectors. Based on a simulation study, we found that, except for low frequency part of the spectrum (0-1.85 mHz, or equivalently, spherical harmonic degrees <10), for which the radial component of inter-satellite velocity vector is the main source of the errors, the approximation error of range-rate and range-acceleration remains <8% of the signal. Considering the KBR ranging noise, it is feasible to accurately compute the along-track potential and LOS acceleration difference directly from band-pass filtered range-rate and range-acceleration, respectively, and employ them for analyses concerning the local time-variable gravity fields of the Earth. We present the results from real GRACE KBR data analysis and applications to local refinement of the GRACE monthly gravity solutions. We also discuss the increased sensitivity to gravity signals by virtue of altitudes lowered down to 350 km in 2016 from the nominal altitude of 500 km.

*G03-3-04
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Evaluating strategies for mitigating aliasing errors in GRACE-like satellite missions

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The aliasing of tidal and non-tidal geophysical signals with frequencies of less than one month into the monthly time-variable GRACE gravity field solutions is an often observed but only partially understood phenomenon. With increasing sensor accuracy (for example, GRACE-FO), the aliasing errors have been identified as the major stumbling blocks for the geophysical applications of satellite gravimetry data. While aliasing affects all spherical harmonic coefficients, their impact on the higher harmonic degrees and orders can be reduced via parameter pre-elimination of low-degree sub-monthly (two-day) solutions often denoted as the Wiese-approach. In this study, we specifically look at how the Wiese-approach handles the aliasing errors, thereby analysing its mechanism in reducing aliasing errors. The Wiese-approach is implemented in the gravity field recovery process via the acceleration approach. In preceding studies, only the along-track acceleration has been used. Here, we demonstrate the benefit of the cross-track and the radial components of the acceleration vector in mitigating the aliasing errors. By using a noise-free simulation, we are able to specify upper bounds for the aliasing errors.

*G03-3-05
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

GRACE de-striping by biharmonic thin-plate splines on the sphere

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If gravity field solutions are deduced from satellite observations, the gravity field information is only available along the ground tracks of the satellite.
Implicitly, a global spherical harmonics solution leads to polynomial interpolation between these tracks.
The oscillation tendency of polynomial interpolation contributes to the undesired striping effect in monthly GRACE solutions.
In the paper an alternative interpolation strategy is tested, which fulfills two requirements
i) It reproduces the observations along the tracks and
ii) it is as smooth as possible between the tracks.
If smoothness is understood as minimal bending energy of an elastic membrane, the strategy results in an spherical thin-plate spline interpolation.
The interpolation problem is solved in two independent ways:
1) As the direct solution of the variational problem and
2) as the solution of the corresponding Euler equation.
In our case the Euler equation is the biharmonic equation on the sphere. For this equation a consistent finite differences approximation is developed and numerically implemented.
Compared to Gaussian smoothed spherical harmonics solution the thin-plate spline solutions shows a better consistency with the observations along the tracks.

*G03-3-06
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SLR monthly gravity solutions using the C5++ software

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This study presents monthly gravity solutions up to degree and order 4 for the period 1993-2015 derived by Satellite Laser Ranging (SLR) data using the C5++ software [Otsubo et al., 1994]. Here, we apply the following modifications to the previous solutions by Matsuo et al. (2013). First, Range bias is estimated for per station and per satellite. Secondly, station coordinates are solved for using no-net-rotation constraints. Thirdly, non-tidal effects for atmosphere, ocean, hydrology are corrected using geophysical fluid models. Last, one-per-rev empirical accelerations are estimated in along-track and cross-track. Consequently, our new SLR solutions exhibited better consistency with those from Gravity Recovery And Climate Experiment (GRACE) than the previous solutions in the degree 3 and 4 components. The improvements of SLR gravity solutions provides further insight into the mass variability of the earth prior to the launch of GRACE in 2002.

*G03-4-01
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Mapping probabilities of extreme continental water storage changes from space gravimetry

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Using data from the Gravity Recovery and Climate Experiment (GRACE) mission, we derive statistically robust 'hotspot' regions of high probability of peak anomalous - i.e. with respect to the seasonal cycle -- water storage (of up to 0.7 m one-in-five-year return level) and flux (up to 0.14 m/mon). Analysis of, and comparison with, up to 32 years of ERA-Interim reanalysis fields reveals generally good agreement of these hotspot regions to GRACE results, and that most exceptions are located in the Tropics. However, a simulation experiment reveals that differences observed by GRACE are statistically significant, and further error analysis suggests that by around the year 2020 it will be possible to detect temporal changes in the frequency of extreme total fluxes (i.e. combined effects of mainly precipitation and floods) for at least 10-20% of the continental area, assuming that we have a continuation of GRACE by its follow-up GRACE-FO.

J. Kusche et al. (2016): Mapping probabilities of extreme continental water storage changes from space gravimetry, Geophysical Research Letters, 43, 8026–8034

*G03-4-02
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Glacier melting and GIA in Alaska estimated from joint GPS, ICESat and GRACE measurements

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The Alaskan Mountain glacier is one of the largest glaciers on the Earth excluding the polar ice sheets over Antarctica and Greenland. However, it is difficult to quantify of the glacier melting in Alaska due to the limited and high-cost traditional observations of the glaciers. Although Gravity Recovery and Climate Experiment (GRACE) can estimate the glacier mass change, but with large uncertainty in GIA, while ICESat needs the density of Alaskan glacier volume change. In this paper, GPS, ICESat and GRACE measurements from 2003 to 2009 are for the first time jointly used to estimate average density, GIA and glacier mass loss. An optimal density of glacial volume change with 750 kg/m3 is estimated to fit the measurements. The glacier mass loss is -57.5 6.5Gt by converting the volumetric change from ICESat. Furthermore, the GIA is also estimated after correcting the ice mass loss signal in GPS and GRACE measurements.

*G03-4-03
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Spatio-temporal downscaling of GRACE water storage changes data at catchment scale

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The launch of the gravity mission GRACE satellites in 2002, caused a quantum leap both in hydrological understanding continental scale systems and their interactions as well as for applications. GRACE captures water storage change over landmasses, which is a useful indicator of climate variability and human impacts on the environment. The application of time variable gravity from GRACE for hydrological purposes has been growing. Recent achievements about the dynamic changes in groundwater highlight the importance of GRACE for hydrological applications. However, the spatio-temporal resolution remains the biggest bottleneck in applying GRACE-derived water storage changes to a wider hydrological use on regional catchments and shorter time scales as often needed for river basin management.
Although the spatio-temporal resolution of GRACE is limited by its orbit configuration, one can downscale water storage variation at catchment scale by assimilating the data of different storage compartments with a higher temporal and spatial resolution. This study attempts to develop a statistical based algorithm to achieve a realization of GRACE water storage with better temporal (less than a week) and spatial scales (~100 km), consistent with auxiliary observations. We use observations of hydrological and hydro-meteorological fluxes e.g. precipitation, runoff and moisture flux divergence. We also use surface water storage and soil moisture storage products. We estimate surface water storage by combining water level from satellite altimetry with the surface water extent from satellite imagery. We obtain spatio-temporal variable soil moisture storage from dedicated satellites e.g. SMOS ASCAT.

*G03-4-04
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

The potential of GRACE gravimetry to detect heavy rainfall-induced impoundment of a small reservoir in the upper Yellow River

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Artificial reservoirs are important indicators of anthropogenic impacts on environments, but their gravity effects have been seldom studied. Here, satellite gravimetry Gravity Recovery and Climate Experiment (GRACE) is utilized to detect the gravity effect of the Longyangxia Reservoir (LR) situated in the upper stream of the Yellow River. Heavy precipitation in the summer of 2005 caused the LR water storage to increase 37.9 m in height or 13.0 Gt in mass. Three different GRACE solutions from CSR, GFZ and JPL and three different filters (an anisotropic decorrelation filter DDK4, Gaussian filter and a decorrelation filter) are compared here. In this case, CSR solutions have the highest signal-noise-ratio and DDK4 shows the best ability to reveal the expected gravity signals. We obtained 109 combinations of inundation area measurements from satellite imagery and water level changes from laser altimetry and in situ observations to derive the area-height ratios in the LR, which agrees well with an alternative method based on the digital elevation model. After removing simulated gravity signals caused by mass changes in the LR, the root mean square of GRACE series in the LR is reduced by 31.1%. If the residuals are totally attributed to GRACE errors, the standard deviation of GRACE observation in this study spot is estimated to be 3.1 cm. With an area of 383 km2, the Longyangxia Reservoir is the smallest signal source reported to be detected by GRACE.

*G03-4-05
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Detection and interpretation of multi-annual mass variation in GRACE monthly gravity solutions

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The GRACE mission provides monthly gravity field solutions for nearly 15 years with very few gaps in the consecutive series of gravity field models. The time series of gravity field models provides primarily a tool for annual and sem-annual mass variations. The length of the data already enables investigations of variations on multi-annual periods. The non-unique sampling of the epochs calls for an appropriate method for determining the multi-annual signal; for the purpose Burg spectrum, modified periodogram, Thompson's multitaper method and Lomb–Scargle periodogram has been adapted. Regions of statistically convincing variations in the 2-10 year periods has been identified. In most cases at these regions the mass variation was found to be related to the El Nino/La Nina events.

*G03-5-01
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

What GRACE/GRACE-FO satellite gravity may tell about the atmosphere (and what not)

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In this presentation we would like to discuss the present benefit and future potential of satellite gravity observations, as obtained from the satellite mission GRACE and its successor GRACE-Follow-On (GRACE-FO), for studying the atmospheric water cycle. In the first part of the presentation, we will show recent results of using GRACE to constrain atmospheric water budgets. GRACE-derived water storage changes (in combination with observed runoff) can be used to solve for the vertical water flux deficit of precipitation (P) minus evapotranspiration (E), which links the terrestrial and the atmospheric water balance equations. This relates gravity change to moisture flux divergence and water vapor change and thus provides, in principle, a link between GRACE/GRACE-FO and (area-averaged) GNSS integrated water vapor observations that may be exploited in the future. We will show that such an independent estimate of P minus E can be used to constrain land-atmosphere fluxes from monthly time scales to decadal trends and even provides meaningful flux information down to daily time steps.

In the second part of the presentation, we would like to give an outlook towards the potential of using satellite gravity data directly for the estimation of atmospheric water mass changes. On the basis of ERA-Interim data, we provide a first assessment which suggests that an anticipated future double-pair gravity mission would be sensitive to 'feeling' atmospheric water mass (water vapor) variations. However, whether these (faster) variations could be separated from dry air mass variations through modeling needs to be investigated. If possible, this would offer a completely new tool for validating atmospheric analyses and for improving engergy and mass budgets in models.

*G03-5-02
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Uncertainty of GRACE-borne long periodic and secular ice mass variations in Antarctica

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Glacial ice mass balance of Antarctica can be determined by monthly gravity field solutions derived from GRACE observations. The present investigation delivers an error estimation of the long-periodic and secular variations by determining the linear trend of the observed surface mass anomaly series. The analysis focuses on unavoidable error sources and disregards the consequences of the methodology. Among the error sources, the error of the timing of the trend fitting, the error of the glacial isostatic adjustment correction, and the error of the atmospheric correction of the GRACE monthly solutions are discussed. The investigation concludes that apart from West Antarctica, Wilkes Land, Queen Maud Land and Enderby Land no reliable trend estimates of ice mass variation can be expected, thus any results should be treated with care.

*G03-5-03
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Ocean tide alias spectrum estimation for satellite gravity missions

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Spaceborne gravimetry missions like GRACE suffer from ocean tide alias errors which can be understood into two steps: undersampling of the ocean tides from satellite orbit and recombination of the satellite measurements over time and space while recovering the gravity field. Although ocean tide models are used for de-aliasing during the gravity field retrieval, the uncertainty in those models will directly alias into the recovered gravity field. If the aliasing frequencies of each tidal constituent would be known, ocean tide alias errors can be mitigated in a post-processing mode. Hence, it is crucial to evaluate the alias periods with respect to the type of satellite mission and to field recovery strategy. Here we develop an approach to estimate the alias spectrum of ocean tide errors based on the abovementioned two steps, taking both satellite orbit sampling and recovery process into consideration. Apart from a GRACE-type single-pair mission, the alias spectrum of a so-called Bender formation is investigated. The latter double pair formation is considered to be the most promising type for future gravity missions and deserves a closer look.

*G03-5-04
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Seasonal water mass variation in the Japan Sea from satellite gravimetry: Comparison with GNSS and seasonality in earthquake occurrences

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Since the launch in 2002, most researches with the GRACE satellites have focused on gravity changes on land, but its increasing time span enables us to discuss time-variable gravity in the ocean, e.g. seasonal water mass changes in the Red Sea (Wahr et al., 2014). Here, we study seasonal mass changes in the Japan Sea (the East Sea of Korea) using the GRACE data 2002-2016 (Level-2 RL-5 data from CSR). By analyzing the GSM files, we found the gravity maximum and minimum in November and June, respectively, with the peak-to-peak amplitude ~10 cm in equivalent water depth. Then we added back the GAD files to recover the original gravity changes in the ocean. Oddly, GSM + GAD resulted in a smaller seasonal change with amplitude of ~4 cm. This means that the non-tidal ocean mass change model used for the GAD files is incorrect in the Japan Sea.
We compared the GRACE data with the tide gauge records in the Japan Sea, and found that tide gauge showed amplitudes several times as large and the maximum in late summer. This suggests that the seasonal sea surface height changes mainly reflect thermal expansion of warm water above the thermocline rather than the real water mass changes. Winter snow also causes seasonal gravity changes in NE Japan with a sharp peak in February. GNSS stations in NE Japan show complicated seasonal movements coming partly from the sea water and partly from the snow. We further discuss the causal relationship between seasonal water mass changes in the Japan Sea and seasonal changes in seismicity in the plate boundary running along the eastern margin of the Japan Sea, i.e. major earthquakes occur during three months May, June and July there.

*G03-5-05
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Seismic gravity changes of the 2004 Sumatra-Andaman earthquake and static gravity anomaly

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The 2004 Sumatra-Andaman earthquake is the first very large earthquake after the launch of the GRACE satellites in 2002. In this study, we analyzed the time series of the gravity changes using the latest GRACE data sets. The result suggests that the postseismic gravity changes of the 2004 Sumatra-Andaman earthquake have almost ended. The observation data can help us determine time scales of the postseismic gravity changes and constrain viscosity structure of the upper mantle. Moreover, it may allow us to research interseismic gravity changes because the static gravity anomaly is formed by the repeat of inter-, co-, and postseismic gravity changes and the static anomaly and co- and postseismic gravity changes are being revealed.

*G03-5-06
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Continuous time variations in relative gravity and tilt, observed by a CG-3M gravimeter during the inflation event at Sakurajima Volcano on August 15, 2015

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Continuous gravity observation is one of the most powerful methods to monitor mass redistributions in volcanoes. In Japanese volcanoes, absolute gravimeters have detected gravity changes of less than 10 microGal originating from volcanism, with those time period of more than a few days (e.g., Kazama et al., JGR, 2015). However, absolute gravimetry cannot precisely detect short-period (< one day) gravity changes due to the low signal-to-noise ratio in the high frequency domain. On the other hand, broadband volcanic phenomena have been monitored by other geodetic observations at many active volcanoes (e.g., Iguchi et al., JVGR, 2008). If the short-period volcanic gravity signals can be detected by continuous gravity observations other than absolute gravimerty, volcanic phenomena will be minutely discussed in terms of mass redistributions.
We were thus motivated to monitor continuous relative gravity changes at high time resolution in Sakurajima Volcano, one of the most active volcanoes in Japan. We installed a CG-3M relative gravimeter (serial number: 9403248) in September 2010, and started collecting relative gravity values at one-minute interval. After the corrections of gravity disturbances such as instrumental drift and tidal gravity changes, we succeeded in detecting a rapid gravity decrease of -5.86 microGal during the rapid inflation event on 15 August 2015. This gravity change is smaller than the typical observation error of relative gravimeters (~10 microGal), but the high-frequency measurements of relative gravity contributed to the detection of the small gravity change in the case of Sakurajima Volcano. We also found that the gravity change was consistent with one of the dike intrusion models provided by Geospatial Information Authority of Japan (2015) if the density value of 0.97 +/- 0.37 g/cm3 was assumed, which implies the drastic foaming of the intruded magma.

*G03-P-01
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ESA's Studies of Next Generation Gravity Mission Concepts

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The presentation addresses the preparatory studies of future ESA mission concepts devoted to improve our understanding of the Earth's mass transport phenomena causing temporal variations in the gravity field, at different temporal and spatial scales, due to ice mass changes of ice sheets and glaciers, continental water cycles, ocean masses dynamics and solid-earth deformations.
The ESA initiatives started in 2003 with a study on observation techniques for solid Earth missions and continued through several studies focussing on the satellite system, technology development for propulsion and distance metrology, preferred mission concepts, the attitude and orbit control system, as well as the optimization of the satellite constellation. These activities received precious inputs from the in-flight lessons learnt from the GOCE and GRACE missions. More recently, several studies related to new sensor concepts based on cold atom interferometry were initiated, mainly focussing on technology development for different instrument configurations (GOCE-like and GRACE-like).
The latest results concerning the preferred satellite architectures and constellations, payload design and estimated science performance will be presented as well as remaining open issues for future concepts.

*G03-P-02
IAG Symposium / IAG02. Gravity field / G03. Time variable gravity field

Combination of monthly gravity fields on normal equation level

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In the frame of the Scientific Combination Service of the European Gravity Service for Improved Emergency Management (EGSIEM), monthly gravity fields of different analysis centers are combined on normal equation (NEQ) level. While common standards for reference frame, Earth rotation and satellite geometry ensure consistency of the NEQs, the different processing centers are free to apply their own processing strategies and to select different background models for de-aliasing and signal separation. The applied noise models are very inhomogeneous, too, and consequently standard procedures for NEQ combination like Variance Component Estimation fail. We present an alternative NEQ combination strategy where relative weights are defined based on the solution noise, as determined by pairwise comparisons of the individual contributions on solution level. We further investigate combination approaches where the individual NEQs are scaled prior to combination, with the goal to reach homogeneous levels of formal errors.

*G03-P-03
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GNSS-based calibration of GRACE accelerometers

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In this study, two approaches for the determination of total non-gravitational accelerations acting on GRACE were investigated. To investigate two approaches, GRACE Level-1B data including accelerometer sensor data, GNSS based positions and star camera data was used. In the first approach, usual surface accelerations acting on the satellite were taken into account. In a second approach, the total acceleration, consisting of a gravitational and non-gravitational contribution, was first determined from the GNSS-based precise orbit data by means of smoothing polynomial and differentiation. Then the gravitational contribution determined by state of art models was removed to determine the non-gravitational part.

The results of these two methods were used to calibrate the linear acceleration measurements on-board GRACE. Daily constraint-free biases and scale factors were determined for two time periods including three month data with a different solar activity. The quality of the results, especially of the second approach is highly dependent on the solar activity and therefore the magnitude of the non-gravitational reference acceleration. The results show that calibration parameters for along track direction can be determined more precise without any information about satellite properties and atmospheric conditions. Constraints have to be applied to get more realistic calibration parameters for axes with a smaller contribution.

*G03-P-04

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Comparison of short-term iGrav superconducting gravimeter observations with local and global hydrological models

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Hydrological mechanisms have been identified as the most complicated environmental effect on gravity signals. In this study, several sources of local and global hydrological observations are used and compared in order to obtain the 10 nms-2 accuracy for the iGrav's measurements needed in many geophysical applications. Six months of stationary measurements with Canada's first iGrav superconducting gravimeter (SG), collected from 31st October 2011 to 1st May 2012 at the University of Calgary, supported by A10 absolute measurements for calibration purposes, are processed and corrected for environmental interferences. After calibration, unwanted signals due to human activities, and natural environmental effects such as Earth tides, ocean loading, atmospheric pressure, polar motion, seismic events, etc., were removed from the iGrav's raw gravity signal. Residual gravity values increased by 50 nms-2, which agrees with the gravity effect of accumulated precipitation obtained by using an empirical admittance factor of 4.2 nms-2/cm. Groundwater level changes also demonstrated high correlation with the high frequency gravity variations. The gravity effect of groundwater level changes was calculated from a Bouguer slab model. The temporal variations of the integrated gravity signal are compared with filtered CSR GRACE monthly mass change solutions. Average soil moisture contributions from global land hydrology models, such as the GLDAS NOAH model with spatial resolution of 0.25 degrees and temporal resolution of 3 hours, are also analyzed. The results indicate that the monthly variations of groundwater storage effect in the iGrav's residual signal can be recovered perfectly by GRACE observations or local and global hydrological models with an accuracy of 8.5 nms-2.

*G03-P-05
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Evaluation and Analysis of Ground Water Level Changes and Water Budget in the Northeast Poland

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Water is one of the most important component of the environment, having a direct effect on the maintenance of life on the Earth. In this paper, the analyses of changes of groundwater level, water budget and all the parameters included in these quantities, were performed on the area of northeastern Poland, in the period of 2003 – 2016.

The groundwater level (GWL) changes were computed on the basis of the mean Terrestrial Water Storage (TWS) values determined from GRACE observations, completed with data acquired from the Global Land Data Assimilation System (GLDAS). TWS data have spatial resolution of one degree, and temporal resolution of one month, therefore the calculated changes of GWL do also refer to such resolution. The obtained results were evaluated by the comparison with the data acquired from the Hydrological Annual Reports of Polish Hydrological Survey.

*G03-P-06
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A novel approach to study ice mass change by integration of satellite data in Greenland and Antarctica

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For the time being there is an exceptional opportunity of achieving simultaneous and complementary data from a multitude of geoscience and environmental near-Earth artificial satellites. These satellite missions allow significant contributions in understanding the climate change. There are many indications for climate change, e.g. sea level rise, ice melting and temperature change. Ice melting is one of the most important indicators in the context of global warming. Therefore, modelling of the Earth's mass distributions due to the ice melting and the temporal changes of such masses, are very important in studying sea level rise. Such study will improve our capability to understand, monitor and predict geophysical/geological processes which are affected by mass changes. The overall goal of this study is to specifically study Earth's surface mass changes due to ice melting in Greenland and Antarctica. The goals will be achieved by analyzing GRACE data, ICEsat data and integrating the results with other In-situ data. For this study we used the GRACE data during the years of 2003 to 2017 and then we determined the rate of the ice mass change, using time series analysis explained in Sjoberg and Bagherbandi (2017). Using the obtained ice melting rate from GRACE data we are able to model near Earth surface mass density changes, according to Sjoberg and Bagherbandi (ibid). Preliminary results show average surface mass changes are -413+-23.9 and 26+-5.9 kg/m^2 per year in Greenland and Antarctica, respectively. The changes will affect the sea level, hence the mass changes are compared with sea level rise obtained from satellite altimetry missions (e.g. Jason 1 and 2). Also the results will be verified by In-situ data like GLDAS (Global Land Data Assimilation System), land surface temperature (Rodell et al. 2004 and Swenson et al. 2006) and other remote sensing satellite missions such as the ICEsat mission.

*G04-1-01
IAG Symposium / IAG03. Earth rotation and Geodynamics / G04. Earth rotation and geodynamics

Limited True Polar Wander as evidence that Earth's non-hydrostatic shape is persistently triaxial

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Earth's spin axis follows the maximum moment of inertia axis of mantle convection, with some delay due to adjustment of the rotational bulge. Here we compute this axis for geodynamic models based on subduction history, assuming constant slab sinking speed, with another contribution due to thermochemical piles. For a wide range of parameters, a large shift of approximately 90 degrees is predicted around 80 – 90 Ma. It can be largely attributed to a change in circum-Pacific subduction from predominantly in the North and South towards East and West. Actual amounts of true polar wander are much smaller, pointing towards additional inertia tensor contributions, possibly due to slabs in the lowermost mantle below both polar regions. These slabs would have been subducted before approximately 150 Ma, when plate motions in the Panthalassa basin are largely unknown. Matching predicted and observed true polar wander can serve at constraining such plate motions.

*G04-1-02
IAG Symposium / IAG03. Earth rotation and Geodynamics / G04. Earth rotation and geodynamics

Short-term Angular Momentum Forecasts for Polar Motion Prediction

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The Earth System Modelling group at GeoForschungsZentrum (GFZ) Potsdam provides operational 6-day forecasts of Earth rotation excitation due to atmospheric, oceanic, and hydrologic angular momentum changes. These EAM forecasts extend the 40 years long EAM series for 6 days into the future with a temporal resolution of 3 hours for both AAM and OAM. A set of 6-day EAM hindcasts from 2016 to 2017 for Earth rotation forecasts reveals positive prediction skills for up to 8 days into the future. Compared to the IERS predictions of bulletin A, the introduction of the 6-day EAM forecasts improves the prediction for more than 10 days into the future for both polar motion and length of day variations. Thus, not only the AAM forecasts as currently used for UT1 predictions in bulletin A, but also OAM forecasts and to a smaller extent HAM forecasts improve polar motion prediction, in particular for lead-times between 2 and 8 days. We will also report about early results obtained at Observatoire de Paris to predict polar motion from the integration of GFZ's 6-day EAM forecasts into the Liouville equation in a routine setting that fully takes into account the operational latencies of all required input products.

*G04-1-03
IAG Symposium / IAG03. Earth rotation and Geodynamics / G04. Earth rotation and geodynamics

Geophysical interpretation of long-term polar motion

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Polar motion represents the constant motion of the Earth rotation pole position in the terrestrial reference frame, and is driven by mass movement and redistribution within the Earth system, under the conservation of angular momentum. Polar motion has been accurately measured by a multi-technique observing program of international scope, with an accuracy reaching ~0.03 milliarcsecond (mas) over variations of up to few hundred mas. Observed polar motion at different temporal scales can be used to study mass changes in different components in the Earth system, including the atmosphere, ocean, hydrosphere, cryosphere and solid Earth. While at interannual and shorter time scales, polar motion is mainly driven by air and water mass redistribution and movement in the atmosphere, ocean and hydrosphere, ice mass change from polar ice sheets and mountain glaciers and non-steric global eustatic sea level change play an important role in driving polar motion at decadal and longer time scales. Solid Earth mass redistributions associated with Glacial Isostatic Adjustment (GIA) and tectonic movement are believed to be the dominated contributors to long-term polar motion (i.e., linear trends in most studied time frames). Using over 14-years of GRACE satellite gravity measurements and climate model predictions, here we provide a comprehensive analysis of geophysical excitations of polar motion from different components of the Earth system, with a focus on interannual and longer time scales. The extended record of GRACE time-variable gravity measurements offer a unique means for people to better understand geophysical excitations of polar motion at a broad band of frequencies, and provide observational constraints on model predicted polar motion excitations, such as those from GIA and pole tide (i.e., rotational deformation).

*G04-1-04
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Hydrological excitation of polar motion by different representations of Earth's gravity field

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The impact of continental hydrological loading from land water, snow and ice, on polar motion excitation, is difficult to estimate and is strongly needed for a full understanding of the excitation of polar motion. These global circulation of surface geophysical fluids induces Earth's gravity field changes.
Mass concentrations parameters and spherical harmonics have been widely used to model variations in planetary gravity fields. Variations in water storage on land affect the time dependent Earth's gravity field as well and can be estimated from Gravity Recovery and Climate Experiment (GRACE) satellite mission and hydrological models.
Firstly, the geographical patterns of terrestrial water storage (TWS) variations determined from GRACE data, as a global mascon solutions and from spherical harmonics coefficients, will be compared to each other and to TWS determined from Global Land Data Assimilation System (GLDAS) hydrological model.
Next, different estimations of hydrological excitation functions of polar motion (Hydrological Angular Momentum - HAM) will be investigated using either monthly TWS data, spherical harmonics as well as mascon parameters representations of Earth's gravity field derived from GRACE mission. Simultaneously, estimations of HAM from GLDAS hydrological model will be done.
Afterwards, we estimate the hydrological signal in geodetically-observed polar motion excitation as a residual by subtracting the atmospheric - AAM and oceanic - OAM contributions. Finally, the hydrological excitations are compared to these hydrological signal from the observed polar motion excitation series residuals.
In this study, linear trend, decadal, inter-annual, and seasonal variations of hydrological excitation functions of polar motion, determined from different representations of Earth's gravity field, are compared to each other. This way, a comparison of HAM estimation strategies from mass concentrations, harmonics coefficients and TWS changes will be investigated.

Global and regional comparison of hydrological excitation functions of polar motion by GRACE data and climate models

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Explaining the hydrological part of the observed polar motion excitation has been a major challenge over a dozen years. The terrestrial water storage (TWS) excitation of polar motion - hydrological angular momentum (HAM), has been investigated widely using global hydrological models, mainly at seasonal timescales. However, the results from the models do not agree among themselves and do not fully explain the role of hydrological signal in polar motion excitation. Throughout the past decade, the Gravity Recovery and Climate Experiment (GRACE) has given an unprecedented view on global variations in TWS.

Our investigation is focused on the influence of Terrestrial Water Storage (TWS) variations obtained from Gravity Recovery and Climate Experiment (GRACE) satellite mission as well as from hydrological and climate models on polar motion excitation functions at decadal, inter-annual and seasonal timescales. The global and regional trend, seasonal cycle as well as some extremes in TWS variations are considered here.

Here TWS are obtained from the monthly mass grids land GRACE Tellus data: GRACE CSR RL05, GRACE GFZ RL05 and GRACE JPL RL05. As a comparative dataset, we also use TWS estimates determined from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models and Global Land Assimilation Data System (GLDAS) hydrological models. The TWS is estimated in two ways: firstly, as a difference of total precipitation, evapotranspiration and total water runoff and secondly, as the sum of soil moisture in all layers, accumulated snow, and plant canopy surface water.

Our studies include two steps: first, the determination and comparisons of regional patterns of TWS obtained from GRACE data, climate and hydrological models, and second, comparison of the regional and global hydrological excitation functions of polar motion with a hydrological signal in the geodetic excitation function of polar motion.

*G04-2-01
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On application of the Kalman filter for high resolution estimation of Earth orientation parameters using the ring laser and VLBI data

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Ring laser gyroscope (RLG) is a promising new technology for directly and continuously measuring changes in Earth orientation; see, e.g., (Schreiber and Wells, 2013, Review of Scientific Instruments 84, 041101) for details. The Sagnac frequency observed by a RLG is sensitive to temporal variations of the instantaneous rotation pole (IRP), while the space geodetic techniques report the terrestrial and celestial motions of the conventional Celestial Intermediate Pole (CIP). The two poles are close to each other when considering variation with periods of the order of weeks and longer, but behave differently at daily and subdaily periods. Here we discuss the possibility of a simultaneous use of the observations of ring laser and very long baseline interferometry (VLBI) for determination of Earth Orientation Parameters with hourly resolution. The combination of RLG and VLBI data is done by a Kalman filter which incorporates the first-order kinematical relationships between the motions of the CIP and IRP.

*G04-2-02
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Corrections to IAU2000 nutation series for consistency with IAU2006 precession

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A central issue in modern nutation and precession theories is to guarantee consistency among their different parts. This fact is motivated because IAU standards considered in the last decades tackle precession and nutation as separated models that are interconnected, but just partially. However, current accuracies in the determination of the EOPs require, at least, adopting some corrections aimed at suppressing the inconsistencies that have been found between IAU2000 nutation and IAU2006 precession. In fact, IERS Conventions (2010) already includes some corrections to amend the IAU2000 nutation series, but they only cover a small part of the inconsistencies discovered so far.

We will present various corrections that must be accounted for to ensure full consistency and discuss their sources. They can be separated into two groups. The first one is due to the changes of the value of the dynamical ellipticity of the Earth, resulting from components of the precession theory not considered or modeled with insufficient accuracy. These changes induce indirect variations of the nutation amplitudes. In addition the change of ellipticity has a part related with the redistribution of mass within the Earth of tidal and centrifugal nature.

The second group stems from some differences assumed for the Earth model in IAU2006 precession with respect to IAU2000 nutation. The main one was the consideration of a constant J2 rate acting on the precession motion. Its incorporation to the nutation model introduces some out–of–phase and mixed secular nutations. Besides, it is also necessary to consider other effects like those related to the changes in some precession quantities, the time–dependent part of the orbital coefficients, etc.

These corrections should be considered in the updating of the IAU/IAG models of the Earth Rotation or incorporated in the most important standards like IERS Conventions to prevent the appearance of systematics associated to these inconsistencies.

*G04-2-03
IAG Symposium / IAG03. Earth rotation and Geodynamics / G04. Earth rotation and geodynamics

EOP prediction based on the Copula method using multi-source data

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Prediction of the Earth Orientation Parameters (EOP) is provided by the International Earth Rotation and Reference Systems Service (IERS) Rapid Service Prediction Centre in USNO, Washington DC. Different methods have been developed and applied for the EOP prediction. However, the accuracy of EOP prediction still is not satisfactory even for a few days in the future. Therefore, new methods or a combination of the existing methods need to be investigated for improving the accuracy of the predicted EOP. Thus, the stochastic methods which analyze and exploit the dependency structure between multivariate data should be studied due to the stochastic nature of the EOP. There is a well-introduced method called Copula and we want to apply it for EOP prediction. The Copula method exploits linear and non-linear dependency between variables and it is a very powerful and efficient tool for dealing with multidimensional data and modeling the relation between parameters.
In this study, we analyze the impact of mass redistribution and movement within the Earth system e.g. solid Earth, atmosphere, ocean, hydrosphere, and cryosphere on EOP to get a more precise and reliable forecasting model. Our preliminary studies illustrate that Copula can be applied for capturing the dependency structure between EOP and angular momentum data. Finally, EOP will be predicted more accurately based on the derived dependency structure by evaluating the conditional distribution function given by the Copula model in the appropriate resolutions.

*G04-2-04
IAG Symposium / IAG03. Earth rotation and Geodynamics / G04. Earth rotation and geodynamics

Excitation study of the observed Chandler wobble based on GRACE and SLR gravity data

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We investigate the excitation of the free Chandler wobble by the large-scale processes taking place in the external fluid layers including the atmosphere, the oceans and the land hydrology. The mass term of excitation is expressed by the so-called gravimetric excitation function estimated from time variation of degree-2, order-1 harmonics of the Earth gravity field, derived from Gravity Recovery and Climate Experiment (GRACE) and the Satellite Laser Ranging (SLR) data. Our first results (Brzezinski and Nastula, presented at GAGER2016 Symposium in Wuhan) indicated that the Chandler wobble observed during 2003–2014 can be fully explained by the GRACE-derived mass term of excitation. Here we extend that study by considering alternative GRACE data sets which are publicly available, like the CNES/GRGS and Tongji solutions. In addition, we include also in the analysis the motion term of excitation taken from different geophysical models.

*G04-2-05
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Determination of accuracy information for effective angular momentum functions derived from gravity field observations

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Variations of Earth rotation are caused by the redistribution and motion of masses within the Earth system. Since 2002, the satellite mission GRACE observes variations of the Earth's gravity field which are caused by mass displacements. Therefore, time variable gravity field models can be used to determine effective angular momentum functions which describe mass-related excitation mechanisms of Earth rotation. By applying suitable filter techniques and masks, not only the integral mass effect on Earth rotation but also the mass effects of the oceans, continental hydrosphere and cryosphere can be studied. The effective angular momentum functions derived from gravity field observations suffer from uncertainties due to (1) the destriping and filtering of the GRACE data, (2) the separation of the individual contributions (leakage effect), (3) the reduction of glacial isostatic adjustment (GIA) and (4) an appropriate replacement of the Stokes coefficients C10, C11, S11 and C20.

In this study we will present a new method to reduce the leakage effect, and via closed loop analysis the impact on effective angular momentum functions is estimated. In order to reduce the GIA effect, different GIA models will be used and compared to evaluate the uncertainties. Due to the fact that the GRACE data processing is performed in the Earth's center-of-mass (CM) frame, the degree-1 Stokes coefficients are zero by definition. But processes at the Earth's surface and interior are referred to a coordinate system attached to the Earth's crust which moves relative to the CM. Therefore, external solutions for C10, C11 and S11 are used to investigate the impact on derived effective angular momentum functions. Due to the low sensitivity of the GRACE K-band measurements on the Earth's flattening the Stokes coefficient C20 obtained from GRACE data are inaccurate. Thus external solutions will be used for C20 to estimate the uncertainties of derived effective angular momentum functions.

*G04-2-06
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Empirical approach to the consistency and accuracy of the current IAU 2006/2000A precession-nutation model

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Due to the gravitational attractions from the Moon, Sun, and planets, the Earth rotation axis shows various periodical motions w.r.t its figure axis. The forced nutations can be precisely modelled and predicted using the IAU 2006/2000A precession-nutation model which relates the International Celestial Reference Frame (ICRF) to the International Terrestrial Reference Frame (ITRF). Currently IAU 2000A/20006 only contains the easiest to predict astronomically forced terms, and thus, the Free Core Nutation (FCN), caused by the fluid outer core and the exchange of angular momentum among the Earth's components, is not included. It causes deficiencies in the IAU 2006/2000A precession-nutation model up to the order of 0.2 mas.
In order to empirically evaluate the consistency and deviations of the aforementioned model we computed several time series of Celestial Pole offsets (CPO) derived from the global analysis of the VLBI sessions since 1990 with varied settings to reflect the impact on the CPO estimates. These series were used to recalculate and adjust the precession constant offset and rate, as well as the main nutation amplitudes of the IAU 2006/2000A precession-nutation model, trying to empirically improve and update the conventional values adopted by the International Astronomical Union (IAU) and the International Association of Geodesy (IAG) and used by the International Earth Rotation and Reference Systems Service (IERS) Conventions 2010. Amplitudes of the FCN were also included in the previous adjustment and compared with other empirical FCN models.

*G04-3-01
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Long-baseline laser strainmeter constructed at the underground KAGRA site in Kamioka as a new tool for monitoring crustal dynamics

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Ground motion and its deformation have been monitored by various instruments with very wide ranges in amplitudes and timescales. Strainmeters measure deformation of the ground by sensing distance between two separated points, and cover crustal observation of small strain changes at low frequencies. However, the strainmeters tend to suffer from local disturbances and instabilities of reference for the distance measurement. Long-baserline laser strainmeters that measure distance of separation of 10-1000m based on highly stable optical wavelength of laser can avoid some of the problems.
A 100-m laser strainmeter [1] at an underground site in Kamioka, Gifu Prefecture, Japan, showed reliable detection of coseismic crustal deformation associated with remote earthquakes and provided estimation of seismic moment based on far-field geodetic observation [2]. It also showed the baseline (100m) was not enough for long-term strain observation because groundwater pressure of seasonal timescale affected the ground strain.
In 2016, a new laser strainmeter with a 1.5-km baseline was constructed at an underground site along KAGRA gravitational wave detector [3] in Kamioka and started test observation. With the long baseline, the strainmeter clearly detected earth tides which almost agreed with theoretical calculations. We discuss its detectability for long-term strain changes in comparison to the 100-m laser strainmeter and prospect for monitoring crustal dynamics using the long-baseline strainmeter.

[1] S. Takemoto et al., A 100 m laser strainmeter system installed in a 1 km deep tunnel at Kamioka, Gifu, Japan, Journal of Geodynamics, 38, 477-488, 2004.
[2] A. Araya et al, Analyses of far-field coseismic crustal deformation observed by a new laser distance measurement system, Geophys. J. Int., 181, 127-140, 2010.
[3] Y. Aso et al, Interferometer design of the KAGRA gravitational wave detector, Phys. Rev. D, 88, 043007, 2013.

*G04-3-02
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First year of gravity signal records with the iGrav-027 superconducting gravimeter

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The new iGrav-027 superconducting gravimeter was successfully installed in early spring 2016 at the Borowa Gora Geodetic-Geophysical Observatory. Since last decade of April a complete gravity signal is recorded providing high quality gravity data for a wide range of applications. The instrument supplements a A10-020 gravimeter as well as a group of LaCoste&Romberg (LCR) gravimeters operating in the Observatory.
This work presents the results of analysis of gravity signal records with the iGrav-027 from the first year of its operation, starting from the scale factor determination and drift characteristics. Scale factor of the iGrav-027 was determined with the use of data acquired with A10-020 and FG5-230 absolute gravimeters as well as LCR relative gravimeters. The instrumental drift will be evaluated by co-location of the iGrav-027 data with conducted on monthly basis absolute gravity determinations with the A10-020 gravimeter.
A comprehensive tidal analysis of the iGrav-027 record along with a more than a 5 year time series acquired with a LCR G1036 gravimeter was performed to obtain a reliable residual signal. Residual signal will be compared with known and available models providing time series corrections for atmospheric and hydrological loading. Residual signal will also be compared with monthly regular absolute gravity determinations with the A10-020 as well as with local hydrological models developed with the use of data from hydrological sensors operating at the Borowa Gora Observatory.
Results of the presented work will be a comprehensive basis for evaluation of long term gravity changes at the Borowa Gora Observatory and for further improvement of the quality of data submitted from the Observatory to IGETS and AGrav databases.

*G04-3-03
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Loading effects caused by storm surges in the Rio de La Plata / Argentina: A model proof by a high resolution gravity time series

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In December 2015, the Superconducting Gravimeter SG038 was put into operation at the Argentine – German Geodetic Observatory (AGGO) located near the city of La Plata, Argentina. Since then, gravity variations are continuously recorded with highest precision and temporal resolution.
By careful preprocessing of the gravity time series of the first year applying a remove-restore procedure, spikes and high frequency disturbances and one step caused by a power failure were corrected. The series was then filtered and downsampled to hourly resolution and atmospheric effects were removed using numerical weather models. Now a detailed Earth tide analysis was performed separating more than 50 wave groups and a treating degree three tide generating potential independently by making use of the capabilities of the latest version V60 of the Eterna software package. Despite these efforts, the residual gravity time series still shows significant non-tidal variations reaching up to several microGal which could not be explained by the applied models but are correlated with extreme weather events.
Wind effects are causing surges at the Rio de La Plata during these events. By using tide gauge observations around the river and a simple empirical astronomical tide model (SEAT) it was possible to compute the propagation of the storm surges landwards from the estuary. The resulting loading effect in terms of gravity shows excellent agreement with the residual gravity time series. This proofs both, the high quality of the gravity time series and the validity of the storm surge model, which allows to isolate gravity effects due to local water storage changes in the gravity record. Perspectively, this model can be used to correct these loading effects also in terms of position changes, which becomes essential as a correction of the results from space geodetic techniques (GNSS, SLR, VLBI) currently established at the observatory.

*G04-3-04
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Constraining vertical land motion of tide gauges (IAG JWG 3.2): combination of velocity fields

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The Joint Working Group 3.2 of the International Association of Geodesy aims at providing contrasted vertical land motion estimates at tide gauges commonly used for long-term sea-level change and for calibration/validation of satellite altimeters.

We present the combination and comparison of available global vertical velocity solutions from GPS and DORIS techniques. Up to 20 individual and 4 combined solutions have been compiled; they include solutions using different GPS processing approaches (differenced and undifferenced), different time series lengths and different approaches to assess velocity uncertainty. The combined vertical velocity solution contains 1132 stations for which at least 3 different estimates were available. After aligning and weighting the solutions, the repeatability of the vertical velocity estimates varies among the stations between 0.1 mm/yr and more than 1 mm/yr, with a median station repeatability of 0.3 mm/yr. These velocity repeatability estimates represent an empirical approach to assess velocity uncertainty and their median value is in agreement with uncertainty assessments accounting for the auto-correlation of the time series.

Estimates of vertical velocity errors for IGS ITRF2014 stations by applying the improved singular spectrum analysis method and environmental loading models

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An accurate removal of the seasonal signals from the Global Positioning System (GPS) position time series is beneficial for the accuracy of the derived velocities. In this research, we propose a two-stage solution of the problem of reliable subtraction of seasonal changes. Firstly, we employ the environmental loading models (atmospheric, hydrologic and ocean non-tidal) and study the seasonal signal (annual and semi-annual) estimates that changes over time using the Improved Singular Spectrum Analysis (ISSA) approach. Then, this model is subtracted from GPS position time series. We studied data from 376 permanent IGS (International GNSS Service) stations, derived as the official contribution to ITRF2014 (International Terrestrial Reference Frame) to measure the influence of applying environmental loading models on the estimated vertical velocity. These loading models show a dominant annual signal and their superpositon reveals amplitudes of up to 12 mm. Having removed the environmental loadings directly from ITRF2014 position time series we noticed the evident change in the power spectrum of GPS time series for frequencies between 4 and 80 cpy. Therefore, we modeled the seasonal signal using the ISSA approach in environmental models and subtracted it from GPS position time series. Finally, we estimated the Dilution of Precision (DP) of the vertical velocities of the ITRF2014 series. For a total number of 298 out of the 376 stations analyzed, the DP was lower than 1. This indicates that when the ISSA-derived curve was removed from the GPS data, the error of velocity becomes lower than it was before.

*G04-3-06
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Vertical velocity profile and possible velocity changes in SW Japan from GNSS data over the last 20 years

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Although GNSS (Global Navigation Satellite System) observations can measure 3-D crustal movement, past studies have focused on horizontal components, i.e. the vertical component has not been well utilized. This is due mainly to the lower signal-to-noise ratio of the vertical components. However, vertical movements are not much influenced by plate motions, and are more straightforward in their interpretation. In Japan, Aoki and Scholz (2003) analyzed vertical crustal movements in the Japanese Islands for 1996-1999. Here we present 20 years of vertical crustal movement data in 1996-2016 from the Japanese dense GNSS array GEONET. Using such long-period data, we analyzed the interplate coupling in the Nankai Trough, Southwest Japan, and estimated the coupling of individual segments of the interface between the Philippine Sea Plate and the Amurian Plate.
Such interplate coupling, in the Japan Trench, is reported to have gradually weakened over 7-8 years before the 2011 Tohoku-Oki earthquake. Classical studies of viscous flow contribution in subduction zones have also suggested that crustal deformation rate may change within an earthquake cycle. In the Nankai Trough, the next inter-plate earthquake is anticipated to occur within the coming years/decades. With the data spanning ~20 years, we could study temporal changes of the vertical velocities. Here we modeled them using quadratic functions of time, and discuss the significance of the quadratic terms. We compared the linear trend and the quadratic components of stations with various distances from the trench, and examined if the quadratic terms show real crustal movements or just a leakage from the movement of the reference point.

*G04-4-01
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Actual Continuous Kinematic Model (ACKIM) of the Earth Crust based on ITRF2014

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The global kinematics of the Earth crust is traditionally represented by geophysical rigid plate models (e.g. NUVEL-1A, DeMets et al. 1994) integrating their motions linearly over geologic time scales (millions of years). The present-day plate motions and deformations in boundary zones are based on these models deriving the plate rotation poles from geodetic station velocities as actual plate kinematic models (e.g. APKIM, Drewes 2009). The denser the geodetic station distribution becomes, the more different plates and inter-plate and/or intra-plate deformation zones are detected. The model PB2002 (Bird 2003) includes 52 plates (instead of 14 in NUVEL-1A) and 13 orogenic zones. But even this increasing structure does not reflect the true crustal deformation obtained from geodetic observations. Larger plates (e.g. North American, Caribbean) do not move rigidly but they are split and present significantly varying motions in different regions. Smaller plates (e.g. Peru, Puna Sierras-Pampeanas, Okhotsk) show strong regional deformations. This paper presents an actual continuous kinematic model (ACKIM) instead of a rigid plate model. Crustal motions in a global 1 deg. x 1 deg. grid are derived from ITRF2014 station velocities in a least squares collocation approach. A no-net-rotation condition with respect to horizontal motions over the entire Earth's surface is included in order to get the model consistent with Earth rotation. The model reflects much better the present-day deformations of the Earth crust than any plate kinematic model.

*G04-4-02
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Comparing Global and Dedicated Plate Angular Velocity Models: the cases of Arabia and South America

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Angular velocities models are necessary to analyse inter- and intra-deformations due to plate tectonics. They permit quantify the magnitude and direction of relative displacement between different tectonic units. The use of inaccurate models can produce incorrect conclusions, particularly at plate boundaries.
In the last decades, many angular velocity models have been produced based on geological/geophysical and/or geodetic measurements. The first ones (e.g., NUVEL-1A and MORVEL) average the motions of tectonic models in the last 3My whereas the geodetic ones (e.g., REVEL and GEODVEL) are representative of the present-day tectonic motions.
Due to the used methodology and data, geologic/geophysical models are only able to be estimated by inverting data for pairs of (or multiple) tectonic plates. This implies that the estimation is always relative to a reference plate. This is not the case for the geodetic models where the used data (normally velocities derived from space-based techniques, particularly GNSS observations) are estimated with respect to a No-Net-Rotation reference frame. Consequently, both approaches are possible: to estimate the angular motion of each plate individually or by inverting a global dataset of velocities.
In this work, we discuss the differences of both approaches by looking at two particular tectonic plates: Arabia and South America. We compare our own dedicated estimations of the plate angular velocities for these plates with the predicted motions given by global plate models and other recent published models. We show that the differences can still be significant when different plate models are considered for the same plate, which can lead to incorrect interpretations.

*G04-4-03
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Modelling of Time-Varying Seasonal Signals in GNSS Time Series

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Most GNSS (Global Navigation Satellite System) coordinate time series contain oscillations of annual and semi-annual periods that are routinely modelled by two periodic signals with constant amplitudes. In reality, the amplitudes of these seasonal signals varies slightly over time. The stochastic properties of the GNSS coordinate time series are well described by power-law noise. Subtracting of the time varying seasonal signals is crucial, since each residual periodicity which is still left in the data naturally will make it appear to be autocorrelated. In this research, we employed 174 IGS (International GNSS Service) stations processed by JPL (Jet Propulsion Laboratory) and showed that the mean variation of the annual amplitude has a standard deviation of 0.8 mm and that for c.a. 15% of stations these variations are larger than 1.0 mm. We performed a quantitative comparison of Wavelet Decomposition (WD), Singular Spectrum Analysis (SSA), Chebyshev Polynomial (CP) or Kalman Filter (KF). Using synthetic time series with realistic power-law noise we showed that ignoring the variations in the amplitude of the seasonal signal results in too large estimates of the spectral index κ of 0.1-0.2 (bias towards flicker noise) and an overestimation of the noise amplitude of about 0.4-1.0 mm/yrκ/4. When the flicker noise amplitude is very low relative to the size of the variations in the seasonal signal, estimating a constant seasonal signal performs worse than any of the methods that try to model varying seasonal signal and can produce an estimated trend error that is overestimated by 0.03 mm/yr. When the noise level is average, the varying seasonal signals can no longer be estimated accurately and one can continue to estimate only a constant seasonal signal. For the JPL-derived GPS data, we noticed a decrease in spectral indices for all coordinates of -0.14 in average and a decrease of trend error of 0.05 mm/yr when time-varying seasonal curves were modelled.

*G04-4-04
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Distribution of interplate coupling in the south of Central and Eastern Java from GPS observation

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Java is one of the many islands at the Eurasian margin in Indonesia in which subduction has been an important influence on its tectonic condition. The subduction process or plate coupling at the Java Trench was considered to be weak. However, two tsunami earthquakes, accompanied by tsunamis have occurred off the south coast of Java, the 1994 Mw7.8 and the 2006 Mw7.8 earthquakes. Given the evidence of this earthquake, it is very important to have detail information of the interplate coupling in particular off the Central and Eastern .
Interplate seismogenic zones in the south of Central and Eastern Java were estimated by using campaign and continuous GPS observation. The observation period is strarting from 2008 to 2016. The GPS analysis indicates that present-day deformation in the south of Central and Eastern Java from is controlled by rotation of Sunda land, postseismic deformation of the 2006 earthquake and the coupling between Indo-Australian plate and Sunda land. The estimated interplate coupling in the Java trench is larger than 50 percent in the Central Java and become bigger to the East.

*G04-4-05
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Seismo-geodetic Behavior of Basic Tectonic Elements in Anatolian Region and Surroundings

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Understanding earthquake and faulting processes requires investigating tectonic-related surface and sub-surface movements through the Earth's crust. In this context, we jointly investigate geodetic and seismological data in Anatolia and surroundings, representing seismically the most active region of Europe. We combine GPS measurements and seismicity between 2006-2016 in order to characterize physical stage of the upper crust at different fault sections. Velocity field has been provided by CORS-TR consisting of 146 GPS stations. Earthquake catalogue has been provided by KOERI at a magnitude detection threshold of 3.0. We produced grid-based distribution of residual velocity field in order to map major inter-plate faults/intra-plate tectonic regimes and their role in whole tectonic process. We also produced a map of seismicity-generated slip distribution along the entire target region. Integrating geodetic and seismological data leads us to quantitatively verify following features: 1-The North Anatolian Fault (NAF) and The East Anatolian Fault (EAF) are the major plate boundaries surrounding the Anatolian Plate. 2- NAF is the most active plate boundary accommodating a slip rates ranging between 7-23.5 mm/yr. 3-The slip rates systematically increase from the east to the west along the fault zone. 4-EAF accommodates relatively a slower inter-plate deformation at an annual slip rate range of 6-9 mm/yr. 5-Anatolian plate reflects internally a very stable tectonic behavior almost for decade. 6- Western Anatolia is however internally deformed as suggested by a variety of slip rates. This probably due to complex fault network developed under large-scale extensional regime. 7-We captured four prominent creeping sections of NAF. 8-In the Sea of Marmara region, where a M>7 earthquake is expected in near future, northern branch of NAF accommodates most of the tectonic slip. 9-Southern branch is however almost inactive based on geodetic and seismological observations.

*G04-P-01
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Length of the Day estimated from DORIS observations

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The Length of the Day (LOD) can be estimated from the DORIS data, when cross track orbit harmonics are not adjusted in the same solution. Our experiment, based on 9 years of the processed DORIS data (2006-2014) , demonstrates a possibility to reach LOD standard deviation around 0.10 msec per day (compared to reference IERS C04 model). The LOD bias is varying between the time periods and reaches the level of low hundredths msec in maximum. We also discuss the accuracy of the single satellite solutions and the multi satellite solution bias variations relations to the changes in the satellite constellation. We present the parameter correlation analysis and the relations between LOD estimation accuracy based on the solution covariance matrix and on the application of time variable gravity field, as well as the impact of the simultaneous estimation of LOD and gravity field coefficient C20.

*G04-P-02
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Revisiting the indirect effect of the triaxiality on the polar motion libration of the non-rigid Earth

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The gravitational action of the Moon and Sun acting on the triaxial Earth gives rise to high-frequency forced nutations of diurnal and subdiurnal periods. Accordingly to IAU 2000 Resolution B1.7 this motion must be described as a part of the evolution of the pole with respect to ITRS, usually referred to as libration in polar motion (IERS Conventions 2010).

One part of that libration is due to the indirect effect of the triaxiality. This effect is related with the fact that the response of the Earth to the lunisolar perturbation, even the zonal one, depends on its structure. It was shown by Escapa et al. (2002, 2003) that the triaxiality of the Earth and its core originate diurnal terms due to their crossing with the (2, 0) harmonic of the gravitational potential. Although the magnitude of some of those contributions was greater than the adopted cut-off level (0.5 microarcseconds), they were not considered in the modelling of polar motion libration due to the uncertainty in the value of the triaxiality of the core existing in that epoch.

In the last years, however, there have been published comprehensive investigations by Chen and Shen (2010), and Sun and Shen (2016), among others, providing accurate estimations of the triaxiality of the Earth and its core. Taking advantage of these results, we recalculate the contributions of the indirect effect of the triaxiality on the libration in polar motion. Our preliminary computations show that these updated amplitudes present a noticeable amplification with respect to their earlier values for some of the newly proposed sets of triaxiality parameters.

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*G04-P-03
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The influence of mantle anelasticity on load response functions

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Predefined response functions are applied to parametrize the effect of load deformation due to seasonal mass redistribution in geodetic correction models, e.g., for GRACE or GPS networks. The correction models are usually based on accepted 1D earth structures like PREM, iaspr or ak135. All these structures represent global means, where, at most, oceanic and continental lithospheric structures are distinguished. One aspect present in the earth's mantle but usually not considered is the impact of anelasticity. As a temperature and material dependent behaviour, anelastic attenuation shows significant lateral variability, especially in the mantle asthenosphere, e.g., at active plate boundaries (Andes, Himalaya) versus passive cratonic regions (North American shield).
In this study, we consider attenuation according to seismological inferences. In order to predict the relaxation of the shear modulus on tidal and seasonal time scales, we extrapolate the constant Q model, which is defined for the seismic band, to these longer time periods.
Based on this approach, we assess the impact on the load Love number spectrum and on the resulting Green's functions. Furthermore, this approach is applied in order to analyse the effect on ocean and atmospheric loading products.

*G04-P-05
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GPS Observation to Identify Bali Back Arc Thrusting

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Historically Bali has been influenced by several destructive earthquakes that caused widespread damages in the south of island and more than 1500 casualties especially from 1917 M 6.6 earthquake disaster. The island is the part of Sunda Shelf which is separated from Java Island by narrow strait called Bali Strait. Although Indo-Australian plate is subducting highly frontal beneath Bali, it should be considered to have low interpolate coupling indicating a low possibility of stress accumulation associated with the plate interface to the south of this island.
This research uses continuous-GPS and campaign-GPS which are distributed over Bali. By using combine analysis of GPS vector velocity, azimuth slip vector from earthquake data and simple inversion modeling, we try to infer interplate coupling on the southern subduction zone and also possible back arc thrusting in the northern part. Our preliminary results show that the combination of moderate coupling on subduction and thrusthing on the back arc contribute to the deformation pattern of the island.

*G04-P-06
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Earth rotation in sight of climate modulations

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We draw attention to the length of day (LOD) and amplitude of the Chandler wobble changes, which show 70-year modulations similar to what can be observed in the mean Earth temperature and sea level. We analyze Chandler wobble phase and amplitude changes, as well as LOD, and their excitation sources, trying to bridge this traditional subject of geodesy with contemporary climatological observations over ocean, atmosphere, and land mass transport. We believe, our epoch of precise observations of the Earth system is already providing an evidence of interconnection between climate processes and Earth rotation changes.

*G04-P-07
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Identifying the land subsidence attributed to the natural gas mining in GNSS time series in Japanese actively crustal deformed area

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Large-scale land subsidence has been observed in the regions of Kujukuri and Shimousa, Kanto District, Japan, caused by continuous mining of groundwater which is refined for natural gas and iodine uses since 1950's. In terms of advanced sustainable development of the mining, urgent research from the view point of geodesy is highly required to evaluate the amount of subsidence caused by the mining. We have successfully identified the land subsidence attributed to the groundwater mining for refining natural gas and iodine from the pumping of groundwater for the agricultural usages and crustal deformations driven by tectonic factors; secular tectonic dynamics, co-seismic offsets, slow earthquake wandering, and the post-seismic deformations of huge earthquakes, applying the time series of GNSS observations analyzed applying GAMIT/GLOBK software. We detach the land subsidence due to groundwater pumping for agriculture uses by focusing their annual periodicity. Then we represent the comparatively short period of time slow earthquakes as Markov process, and segregate it from other causes. We evaluate the amount of crustal subsidence originated from plate collisions under the Kanto District, which widely seen in the Kanto plane before the 2011 Mw9.0 Tohoku-Oki earthquake, and we disregarded it since this kind of land subsidence is an order of magnitude smaller than them caused by the human activities. Finally, we express the time series of the post-seismic activities after the 2011 Tohoku-Oki earthquake as logarithmic, exponential, or combined logarithmic and exponential function models. Thus we enable complicated crustal deformations arising around Kujukuri and Shimousa area to be segregated into the artificial and the tectonic factors, and evaluate the amount of the subsidence originated by the groundwater mining for refining natural gas and iodine.

Constrained Differential Wi-Fi and UWB Measurements for Indoor Cooperative User Localization

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Many personal mobility scenarios require the localization of users within a group or neighbourhood. A solution to this problem is Cooperative Positioning (CP) where the end user localization is performed using its own measurements plus any additional information coming from neighbouring users in the form of inter-nodal ranges or other means. In this study, new differential Wi-Fi positioning approaches based either on DGPS or VLBI are applied for (tri)lateration. By the use of reference station (RS) observations the received signal strength (RSS) measurements of the access points (APs) is corrected to reduce short- and long-time variations of the RSS at the user side. A low-cost implementation is realized using a number of Raspberry Pi units, which serve simultaneously as both APs and RSs emitting and scanning Wi-Fi signals. For the data collection a smartphone application (Android App) has been developed. Furthermore, the use of UWB and its combination with Wi-Fi is investigated to form a networked solution. In the practical evaluation, static and kinematic tests using six users carrying different smartphones are conducted in an indoor lab of approximately 400m2. Five Raspberry Pi's served as reference stations and APs together with another three additional Wi-Fi routers. One user enabled the hotspot function on his mobile device so that the other users can measure the RSS to derive inter-nodal ranges. Additional five UWB units were carried by the users serving as either a reference for the derivation of the inter-nodal ranges or in order to be integrated into the overall positioning solution. Ground truth for these experiments was measured using a robotic total station. It is proven that both DWi-Fi approaches outperform conventional RSS lateration and the integration with UWB further strengthens the CP solution.

*G05-1-02
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ning: Theory and applications

Static and kinematic experimental evaluation of a UWB ranging system for positioning applications

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Ultra Wideband (UWB) is a rapidly evolving radio-based technology leading to low range uncertainty (< 10 cm) even at long (up to hundreds of meters) ranges. Compared to other radio-based technologies, such as RFID and Wi-Fi, the bandwidth characteristics of UWB offer remarkable NLoS functionality and increased multipath resistance which are of great importance for complex indoor environments. This study presents the results of the analyses undertaken for a number of tests using a commercial UWB system both in static and dynamic conditions. Static experiments involve assessing the capabilities of the system in terms of position accuracy (precision and trueness), availability, maximum range operation, as well as examining the influence of antenna orientation and the surrounding environment (e.g. the Fressnel zones) in distance measurements. Kinematic positioning is performed by implementing the multi-lateration technique on a roving UWB node, while vehicle kinematics are recorded using a geodetic (tactical) grade GNSS/INS system to provide the reference trajectory. The UWB position solution is improved through range calibration while range error maps are generated to support statistical analyses. Both an Extended Kalman Filter (EKF) and an Unscented Kalman Filter (UKF) are implemented for trajectory extraction and compared against the reference trajectory to assess their impact on the position solution.

The Database Referenced Navigation Algorithms : A new attempt at combining geophysical DBs and navigation algorithms

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Recently, an alternative navigation method which uses various geophysical database is being studied for compensating for inertial navigation system (INS) errors against the non-global navigation satellite system (GNSS) environment. In virtue of precise geophysical sensors and databases, the precision of the database referenced navigation (DBRN) system is known to be from the few tens, even hundreds of meters. However, the stability of the DBRN dramatically decreases due to the inconsistency of the geophysical DBs. Especially, filter based navigation algorithm sometimes diverges once wrong or over correction occur. Therefore, the way to develop more robust navigation algorithm is still an important question in the DBRN. In this study, two new attempts to combine geophysical DBs or navigation algorithms are tried to improve the stability. Since geophysical DBs show different local characteristics, both terrain and geophysical DBs are applied to estimate the position of the vehicle in the extended Kalman filter (EKF)-based navigation algorithm. Then, the profile matching algorithm which uses stacked terrain information is realized to evaluate the stability of the EKF-based algorithm. Once, two solutions show large differences, the position from the profile matching is selected or used to estimate the new position. The effects of applying two geophysical DBs in the EKF-based algorithm and combining navigation algorithms are evaluated through simulation tests. Especially, the stability of the navigation performance is verified when geophysical DBs changes abruptly or diminutively. Finally, Some discussions on the future works are also included.

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The Estimation of Error Models of MEMS-IMU and its application to develop the GNSS/MEMS-IMU/On-board Vehicle sensor based positioning System

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The determination of the precise position and attitude of a vehicle is an essential issue in ensuring the safety of the driver and pedestrian. Recently, vehicles equipped with various sensors have been introduced to support the safety of drivers. In addition, GNSS/INS integration technology is broadly applied in the field of the mobile mapping system (MMS) and unmanned aerial vehicle (UAV) due to the development of low-cost micro-electro-mechanical system (MEMS). MEMS-based inertial measurement unit (IMU) has an advantage in terms of the small size as well as the low cost, but its error rapidly increases in a short time. Especially, the stability of the position could not be guaranteed in the case of the GNSS signal outage. Therefore, it is necessary to model the behavior of the MEMS-based IMU to maintain the stability of positioning. Also, the way to compensate the error of MEMS-based IMU using supplement sensors is required to improve the precision of the position in the GNSS/INS integration.
In this study, three types of error models, random constant, 1st order Gauss-Markov and 3rd order Autoregressive, were applied to estimate the MEMS-based IMU error. The estimated models were applied as a form of closed-loop in the extended Kalman filter (EKF) based navigation algorithm to compensate the error, and the effect of the models were evaluated based on the static and kinematic experiments. Also, the position, velocity and attitude estimated from various on-board sensors are applied to improve the performance of the navigation when GNSS signal is blocked

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Global GNSS processing based on the raw observation approach

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High-quality global navigation satellite system (GNSS) products, such as precise satellite orbits and clocks, are a requirement for many GNSS applications, e.g. Precise Point Positioning. These products are routinely determined by analysis centers of the International GNSS Service (IGS). In their GNSS processing, these analysis centers make use of the ionosphere-free linear combination to reduce the ionospheric influence. Some of the analysis centers also form observation differences, in general double-differences, to eliminate several additional error sources. The raw observation approach is a new GNSS processing approach that was developed at Graz University of Technology for kinematic orbit determination of low Earth orbit (LEO) satellites and for processing a global ground station network. The raw observation approach offers some benefits compared to well-established approaches, such as a straightforward incorporation of new observables due to the avoidance of observation differences and linear combinations. This becomes especially important in view of the changing GNSS landscape with two new systems, the European system Galileo and the Chinese system BeiDou, currently in deployment.

Graz University of Technology currently generates the following GNSS products using the raw observation approach: precise satellite orbits and clocks, station positions and clocks, code and phase biases, and Earth rotation parameters. The new approach is evaluated by comparing products generated using the Global Positioning System (GPS) constellation and observations from the global IGS station network to the GNSS products of IGS analysis centers. The comparisons show that the products determined at Graz University of Technology are on a similar level of quality to the IGS analysis center products. This confirms that the raw observation approach is applicable to global GNSS processing. Some areas requiring further work have been identified, enabling future improvements of the method.

*G05-1-06
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Improving GNSS RTK and kinematic PPP positioning through extended Kalman filter tuning

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In the past decades, the number of global GNSS data analysis centers and reference stations has consistently increased – from about 100 reference stations in 1995 to more than 500 nowadays. The quality of the orbits, clocks and atmospheric behavior modeling products increased at the same pace. As of February 2017, the final IGS orbits are believed to be accurate at a 2.5 cm level and the clocks at a 75 ps RMS level. Considering as well the increasing quality of GNSS receivers and antennas, often the fine-tuning of positioning estimation for applications demanding high-precision lies in the correct parameterization of the filter. The Extended Kalman Filter (EKF) allows users to set stochastic variations for the parameters to be estimated, such as antenna acceleration, ionospheric, and tropospheric delays random-walk. By under-constraining those parameters with generic values, the error budget is ill-distributed between the different effects on the final estimated position. Also, over-constraining them will force the mathematical model to apportion the same error budget wherever the system allows, often resulting in significant positioning errors. The often overlooked EKF tuning is hereby addressed by a short review of the problem mathematics, followed by experiments. The first dataset is composed of one month of data from the stations UNB3 and UNBJ where different scenarios in RTK and kinematic PPP are analyzed in order to find the specific tuning in a well-known position. The second experiment uses data collected by a GNSS receiver on the top of a vehicle while riding in an urban/suburban environment. The results show 5-10% improvements in accuracy in both RTK and kinematic PPP solutions for the first experiment and indicate a better performance on reconvergence and challenging environments for the second experiment. In conclusion, guiding the EKF with information about the platform and atmosphere can be the difference between achieving or not the desired accuracy.

*G05-2-01
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ning: Theory and applications

Impact of Multi-GNSS analysis on precise geodetic applications

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Today, many GNSS Permanent networks are enhanced from GPS or GPS/Glonass networks to Multi-GNSS networks supporting also the signals of the European Galileo and the Chinese BeiDou satellite system. The additional signals are beneficial to many applications. This paper focus on the impact on precise geodetic applications, such as precise coordinate determination based and daily solutions and also improvements on kinematic precise PPP solutions. Here, results from the complete processing chain are shown – from data collection to analysis.
Swisstopo, the Swiss Mapping agency enhanced its permanent network to Multi-GNSS beginning 2015. A complete MULTI-GNSS data flow based on RINEX3 is established parallel to the RINEX2 data flow mid-2015. Parallel to these developments also the field equipment was replaced after conducting a technical evaluation. All 200 reference stations were measured in 2016 by static Multi-GNSS observations of about 48 hours.
On the analysis side the scientific Bernese Software was updated enabling multi-GNSS capability and making use of the IGS MGEX products (especially the CODE-derived Multi-GNSS orbits). These developments were used to analyse the Multi-GNSS data from the field campaigns as well as to analyse the permanent networks. As first analysis centre in Europe the contribution of daily and weekly solutions to the European Permanent Network (EPN) of EUREF was switched to Multi-GNSS mid-2016.
Intersystem parameters are an important indicator of the compatibility of the coordinates and troposphere parameters between the various satellite systems. Examples will show the order of magnitude these parameters can reach and will demonstrate its impact on the final results.
On the way towards real-time, we show results of kinematic PPP solutions, addressing the possible gain using additional satellite systems.

*G05-2-02
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Assessment of PPP quality for high speed kinematic application.

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Precise Point Positioning (PPP) has been used in several applications and showed quite high accurate results. Normally, such applications are either in static mode or in a quite stable kinematic mode. In this presentation we will access the results of a PPP experiment accomplished during an aircraft flight, in which the velocity reached up to 700 km/h. The reference trajectory was determined using multi relative positioning, providing precision better than 20 cm. The PPP results from the two flights were compared with the reference trajectory. We will present details of the flights, determination of the reference trajectory and the in-house PPP software developed for such application together with the results. From the results obtained so far, we can conclude that, as expected, the quality deteriorates with the aircraft velocity and that most of time accuracy better than 80 cm was obtained for the height component.

*G05-2-03
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ning: Theory and applications

Statistical Analysis of Multi-GNSS Inter-System Biases for Precise Point Positioning Ambiguity Resolution

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Compatibility and interoperability among multi-GNSS constellations are the necessity for reliable multi-GNSS positioning and navigation, thus, attracting great attention from the satellite navigation community over recent years. There are inter-system biases affecting precise point positioning (PPP) ambiguity resolution. While it has been well known that differenced integer ambiguities between satellites are resolvable. in the current PPP ambiguity resolution procedures, due to the multi-GNSS Inter-System Biases, the integer carrier phase ambiguities between satellites within a single constellation are formed, for example, GPS ambiguities and Galileo ambiguities are separate. Such a situation will certainly reduce the performance of multi-GNSS ambiguity resolution due to a relatively weaker geometry than the scenario in which integer ambiguities between any satellites within multi-constellations can be resolved.

In this paper, we will investigate the statistical characteristics of multi-GNSS Inter-System Biases, especially in the carrier phase domain, and design procedures to estimate and accommodate these biases towards the goal to resolve the integer ambiguities between any satellites within the multi-constellation GNSS. For example, in conventional PPP-AR methods, one GPS and one Galileo satellites are chosen as reference satellites to form inner-system between-satellite-single-differencing (BSSD). In this new method, only one GPS satellite will be selected as the pivot satellite to form GPS-GPS inner-system BSSD and GPS-Galileo inter-system BSSD. Experimental results will be presented to show the time variability of these ISBs and compare the PPP-AR performance of this new method and traditional methods.

*G05-2-04
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Quality of GPS, GLONASS, Galileo and BeiDou real-time orbits and clocks

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A constantly increasing number of satellites of Global Navigation Satellites Systems (GNSS) and their continuous modernization allow improving the positioning accuracy and enables performing the GNSS measurements in demanding environments. In order to take advantage of all GNSS and their frequencies it is necessary to get precise orbits and clocks also for new systems. To provide such products Multi-GNSS experiment (MGEX) has been established by the International GNSS Service (IGS). Products ensured by IGS may be used only in post-processing mode due to the latency of these products.
IGS Real-Time Service (RTS) was launched in April 2013 in order to pave the way for obtaining the position in real-time. Products provided currently by IGS-RTS are available only for GPS and GLONASS. Therefore, to enable real-time users to take advantage of all GNSS observations it is necessary to provide orbit and clock corrections for all available GNSS via streams. Centre National d'etudes Spatiales (CNES) is one of analysis centers that provides freely available corrections for all GNSS, including new systems.
The presented work evaluates the availability and quality of real-time corrections. The final products provided by the Center of Orbit Determination in Europe (CODE) and Satellite Laser Ranging (SLR) are used as a reference for the evaluation of real-time products. The 3D orbit RMS, when compared to CODE products, is 5, 10, 19, 18 and 37~cm for GPS, GLONASS, Galileo, BeiDou MEO and IGSO, respectively. The insufficient quality of BeiDou geostationary orbits that reaches above 1~m is inadequate for precise positioning applications. The conducted works are a background for further studies related to the real-time Multi-GNSS processing, e.g. using the proper system-specific weighing of observations in order to achieve reliable multi-GNSS solutions.

*G05-2-06
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High-rate RTK and PPP for precise dynamic displacements determination

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The measurement method applied for the monitoring of the ground and engineering structures' displacements ought to satisfy the highest requirements in terms of accuracy, reliability and availability. These specific demands may be met by the GNSS technique and suited method of signal processing. High precision and availability of high-rate GNSS observations predestine this technology to be applied to the most demanding applications such as small-scale dynamic displacements determination. Thus, GNSS positioning may be used as a reliable source of information on dynamic, different origin deformations, also in real time applications.
In this study both RTK and PPP positioning techniques have been implemented and employed in order to retrieve small-scale high-rate site displacements. Methodology and algorithms applied in self-developed software allowing for precise absolute and relative multi-GNSS positioning were given and supported by the results of conducted experiment. In the experiment were used the GNSS observations derived from high-rate (50 Hz) geodetic receivers and processed using several established scenarios in a RTK and PPP modes. The dynamic displacements were simulated using constructed device responsible for generation of GNSS antenna oscillations with dedicated amplitudes and frequencies. The results indicate on applicability of both relative and absolute positioning techniques to detection of dynamic displacements of the GNSS antenna even at the level of few millimetres after suitable signals processing.

*G05-3-01
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Higher Order Ionospheric modelling campaigns for precise GNSS applications

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The first order ionospheric term (I1) is the main contributor to the ionospheric delay of GNSS observations, compared with the less than 0.1% corresponding to the higher order ionospheric terms. However, higher order ionospheric effects (I2+) are one of the main limiting factors in very precise GNSS processing, for applications where millimetre accuracy is demanded. The consortium of LGP, WUELS, UWM and UPC deals with higher order ionospheric mitigation under the HORION (Higher Order Ionospheric modelling campaigns for precise GNSS applications) project, supported by the European Space Agency. This HORION project is focused on the development of the HORION-PL web service for mitigation of higher order ionospheric terms, thus improving precise GNSS processing.
Within this project we also investigated the impact of I2+ on troposphere delay estimation, long-range relative positioning and autonomous positioning. We selected three networks (global, Polish and Brazilian) and three test period (each one week long, reflecting solar minimum conditions, solar maximum conditions and geomagnetic storm). We also estimated GPS and GLONASS orbit and clock products, that were further used in GNSS processing. We performed each processing in two variants 1) with original RINEX files, and 2) with I2+ corrected RINEX files, to assess the impact of I2+ effects on the results.
The initial analysis of I2+ impact on orbit modelling showed the following RMS of residuals: 1.1 mm, 3.7 mm and 3.3 mm for radial, along and out-of-plane component respectively. For troposphere, the average ZTD difference was -0.06 mm with 0.20 mm of standard deviation, with the extreme ZTD differences reaching 3.4 mm and -4.4 mm. ZTD differences obtained in Brazilian network fluctuates following daily I2+ correction oscillations. In Poland this effect is smaller, due to shorter baselines and lower ionosphere activity.

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Crustal deformation in response to the changing climate

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Vertical crustal movements induced by atmospheric, hydrological, cryospheric, and oceanic load changes are detectable with sub-cm accuracy by precise continuous GPS measurements. Areas subjected to rapid load changes due to icesheet melt, drought, massive groundwater extraction, or lake level drop, are characterized by a dominant non-linear uplift signal. In other areas, seasonal load changes often mask the longer-term climatic signal. Here we present a new method for removing the seasonal signal and extracting the climatic signal from long GPS time series (>15 years). Applying the method to GPS records form western and eastern North America indicates different load change characteristics. In the western US, the seasonal and climatic signals are dominated by hydrological load changes and, consequently, the GPS climatic signal correlates well with the Palmer Severe Drought Index calculated for the same region. In eastern North America the GPS climatic signal in some stations correlates with the North Atlantic Oscillation (NAO) index, suggesting a linkage between decadal scale weather patterns in the Northern Atlantic region and vertical crustal movements, possibly due to ocean and atmospheric load changes. Our results suggest that long continuous GPS observations of vertical crustal movements can serve as independent measures of regional-scale climate change.

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Variometric approach for displacement analysis using Galileo data

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The Variometric Approach for Displacement Analysis Standalone Engine (VADASE)* was successfully applied for seismological and monitoring purposes using GPS observations. The Galileo system, recently entered in the Initial Services operation phase, supplies GPS inter-operable and specific observations that can be used by VADASE.
In this work, the Galileo derived VADASE solutions are inspected to evaluate the impact of the European system. In particular, the combined GPS and Galileo variometric model has been improved in order to consider two receiver clock variations for both the systems. VADASE solutions were, at first, computed using single and iono-free observations from a set of IGS-MGEX sites in order to evaluate the sensitivity of the solutions with respect a static scenario. After, real displacements were investigated using U-blox single frequency receivers. The comparison with the GPS derived solutions was carried out selecting GPS constellations with the same number of satellites and the closest PDOP values to that of the Galileo constellations inspected. The analysis was carried out using broadcast and precise orbits. Standard statistics of the Galileo derived solutions are provided and commented. In general, the solutions are of good quality and essentially comparable to or better than the GPS derived solutions.
The preliminary results enhance the contribution of Galileo system and pave also the way to a wider use of low-cost single frequency receivers for monitoring applications.
Furthermore, a WebApp version of the VADASE software is presented in order to give to the scientific community the possibility to run the variometric approach on RINEX files.

*Colosimo, G., Crespi, M., Mazzoni, A. Real-time GPS seismology with a stand-alone receiver: A preliminary feasibility demonstration (2011) JGR Solid Earth, 116 (11)

*G05-P-01
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Assessment of GNSS and map integration for lane-level applications in the scope of Intelligent Transportation Location Based Services (ITLBS)

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To enable safe and robust Intelligent Transportation Systems (ITS) applications, the integration of different sensors and techniques will certainly be a common reality. One application in this context is the lane-keeping techniques for autonomous driving systems. These systems normally use imagery sensors for lane identification, however imagery systems always depend on light and well structured roads. One potential worldwide autonomous driving technique without any other lane and road detection/identification sensor would be GNSS positions along with accurate map information. However, this fusion depends on the accuracy and reliability of both GNSS positions and map information. The positioning accuracy that Intelligent Transportation Location Based Services (ITLBS) requires for where-in-lane and active control applications are 0.5 m and 0.1 m, respectively. To evaluate the potential of a such fusion, this work proposes an integration of GNSS and map information in the attempt to address the lane-keeping problem. This integration is performed by merging GNSS solutions and lane centerline positions, acquired from aerial orthophotos, into a Kalman Filter and a map-matching approach. To measure the positioning error, or off-track performance, a conversion of positions to the "road domain" is necessary. To evaluate the results, a positioning accuracy limit, considering the road, vehicle dimensions, and the requirements for ITLBS is also proposed. The results showed that 95% of the time the proposed methodology off-track performances were within 1.89 m, in an average of 4 runs. Half of the runs were within 0.75 m, in average, at 95% of the time. Compared to an accurate GNSS Post Processed Kinematic (PPK) mode, an improvement of 10% was achieved.

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Evaluation of digital surface models created from LiDAR and optical sensor data collected with unmanned aerial systems

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Unmanned aerial systems (UASs) are becoming more popular in local scale topographic mapping. The state of the art in topographic UAS mapping is the use of consumer-grade RGB cameras, however, sensor development caused that laser scanners started to be used for this purpose. This work aims on comparative assessment of digital surface models (DSMs) created form data collected with 3 various UAS sensors: Nikon D800 RGB camera, Optris PI Lightweight 450 thermal camera, and Velodyne HDL-32E laser scanner. The evaluation focused on assessing the impact of georeferencing method to created DSM. All data was processed using standard methods. In the case of imagery data a bundle block adjustment (BA) was executed and was followed by image dense matching to create point cloud necessary for DSM modeling. Three types of georeferencing constraints in BA were investigated: ground control point (GCPs) measured with GNSS-RTK technique, image projection centers obtained from onboard GNSS-RTK measurements, and from onboard navigational GNSS solution. In the case LiDAR data, direct georeferencing of the point cloud using post-processed kinematic GNSS/INS solution was executed. Obtained DSMs were compared to the most accurate DSM created from high resolution RGB images georeferenced using GCPs. Results showed that georeferencing method has higher impact to the DSM accuracy than the quality of the sensor. Low quality thermal images georefer-enced using GCPs resulted in DSM of vertical RMSE equal to 17 cm, while good quality RGB images georeferenced with other methods resulted in vertical RMSE equal to 60 cm, however, a significant bias of about 50 cm was observed. It proved that internal accuracy of the point cloud created from RGB images is very high. In the case of LiDAR data, obtained RMSE was equal to 47 cm, but the internal accuracy of the point cloud was much lower than for RGB data. It was caused by lower quality of GNSS/INS solution, especially the orientation.

Improving low-cost GNSS navigation in urban areas using multi-constellation receivers and integrating a Kinect device

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In the last decades, low-cost GNSS receivers have been widely used for navigation purposes. Some of them deliver also raw data, allowing for a more sophisticated processing, such as the double difference approach, and therefore a more accurate positioning, typically at the decimeter level. However, these accuracies can be generally achieved only with a good sky visibility, that is a critical issue in urban areas even using low-cost receivers equipped with a high-sensitive antenna. In this respect, a significant contribution comes from the multi-constellation signal that increases the number of visible satellites. An additional possibility is the integration of the GNSS receiver with a camera or a laser scanner. In fact, the external orientation of the acquired digital images or dense point clouds ultimately provides an estimate of the sensor kinematic position.
In this work, we have first studied the contribution of the different GNSS constellations to the accuracy and the temporal continuity of the estimated trajectory in outdoor urban environment by a low-cost receiver, such as u-blox or NVS devices. The free and open source goGPS software has been used to process the receiver raw data. Then, we have studied the integration of the Kinect device into the navigation system. This device is endowed with a depth camera, as well as a RGB camera, at a cost of about 200$, thus maintaining our main target of realizing a low-cost system. A proper Kalman filter has been implemented for jointly processing the GNSS estimated coordinates and the images of the Kinect cameras. An outdoor experiment has been arranged with the aim of testing the hardware and software system. The results show that the obtained improvement is more significant for the temporal continuity of the trajectory rather than for its accuracy.

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Multi GNSS attitude estimation of UAVs during landing

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Sensor fusion methods are becoming increasingly important in all aspects of commercial aviation, especially in the challenging phases of flight like landing, where ILS, GNSS and vision based sensor sources can be fused. If we would like to enhance the safety of air transport, then it is necessary to improve the navigation system and built -in fault detection of these functions. The attitude estimation has a prominent role of this improvement. The inertial measurement units (IMU) provide data necessary to all navigation tasks, but the drift of the gyroscope and accelerometer sensors decreases the reliability of these measurements, particularly at the low-cost devices.
The main objective of the H2020 VISION project (Validation of Integrated Safety-enhanced Intelligent flight cONtrol) is to validate smarter technologies for aircraft Guidance, Navigation and Control. Within the framework of the project we would like to present an algorithm which estimates the attitude of the aerial vehicle based on single frequency, single baseline, multi GNSS code and phase measurements, to provide a redundant alternative for IMU based attitude data.
The baseline coordinates between the two GNSS antennas and the single-differenced integer ambiguities are estimated by an Extended Kalman Filter (EKF). This EKF algorithm is supplemented with a Baseline Constrained Least-Squares Estimator of the Integer Ambiguities. The heading and the elevation angles of the aircraft are estimated with this method within one degree precision, significantly enhancing the inertial based attitude determination. The method also has the advantage, that the solution is drift free unlike the attitude of the IMU.
This study discusses the computational algorithm and the validation experiment.
Based on the real flight test data, it is examined how single frequency GNSS attitude solution can improve the Guidance and Navigation during landing of the aircraft, which is one of the most hazardous phase of the flight.

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Short-Term Prediction of IGS Real Time Service Data for Continuous GNSS Positioning

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For precise global navigation satellite system (GNSS) positioning, GNSS error components such as satellite orbit and clock errors need to be corrected. The international GNSS service (IGS) provides a real-time orbit and clock estimates (real-time service, RTS) for real-time precise positioning. The real-time performance of the RTS, i.e. accuracy and stability, are analyzed with a long-term data. And the RTS correction availability for the GPS satellites observed in East Asia is analyzed. Since the IGS RTS provides the real-time corrections via the internet, intermittent data loss can occur due to software or hardware failures. In order to make up for possible RTS data loss or delays, several prediction algorithms for the RTS data are developed, which include polynomial extrapolation, autoregressive moving average (ARMA), and machine learning algorithms (neural network and genetic algorithm). The prediction interval is set from 10s to 900s, and the performance of those methods are evaluated and compared. The machine learning algorithms yields a substantial improvement, greater than 25%, over the simple extrapolation algorithms. The error reduction is more significant in the clock prediction than in the orbit prediction. The clock correction has a more stochastic variation than the orbit correction, and the machine learning algorithm is efficient for predicting such a stochastic variation.

*G05-P-07
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Multiplicative random error models: Parameter estimation and error analysis

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Conventional geodetic adjustment theory has been almost always developed on the linear and/or linearized model of measurements. The most important feature of these conventional adjustment methods and theory are that the random errors of measurements are added to the functional models. In other words, the sizes or magnitudes of random errors are independent of the true values of measured quantities. However, in geodetic practice, we know that this assumption is not necessarily always true. For example, we know that the accuracy of an EDM, GPS and/or VLBI baseline is proportional to the length of the baseline itself, which clearly indicates that the random errors of this type are proportional to the measured quantities. From the statistical point of view, such random errors should be multiplied to the functional models and are not additive any more. In this talk, we will extend the conventional model of geodetic adjustment to account for multiplicative errors and/or mixed additive-multiplicative errors. We will address the parameter estimation and error analysis in the linear/linearized model of measurements with mixed additive-multiplicative random errors. More specifically, we will first discuss three least-squares-based methods to estimate the model parameters, namely, least squares, weighted least squares (LS) and bias-corrected weighted least squares. We will then analyze these three methods from the statistical point of view. We construct five estimators of the variance of unit weight in association with the three LS-based methods and compare them, statistically and through numerical simulations. Although LiDAR data have been proved to be of multiplicative nature, they have been treated as if they were of additive random errors. Thus, as a final part, we will simulate a landslide example, which is supposed to be surveyed with LiDAR, to demonstrate how the methods discussed here works and how they can be applied to DEM construction for disaster monitoring.

*G05-P-07
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MINIMUM MEAN SQUARE ERROR ADJUSTMENT, Part 2: The Empirical BLE and the reproBLE for multivariate positioning

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Abstract:
A little while ago, in 2000, Schaffrin showed how the weighted Least-Squares solution (LESS) within a model of direct observations (univariate case) may be improved by applying the minimum Mean Square Error (MSE) principle, either leading to the well established Empirical BLE (Best Linear Estimate) or the novel reproBLE. Here, an attempt will be made to generalize the concept to cover the multivariate case in form of a Gauss-Markov Model. First steps in this direction had been undertaken by Schaffrin in 2008 already, but with emphasis on the optimal choice for the Tykhonov-Phillips regularization parameter. Now, new aspects of any solutions of type reproBLE regarding questions of positioning will be the focus of this contribution.

Reference:
Schaffrin, B. (2000) Minimum mean squared error adjustment, Part I: The empirical BLE and the repro-BLE for direct observations. J Geod Soc Japan 46:21–30
Schaffrin, B. (2008) Minimum mean squared error (MSE) adjustment and the optimal Tykhonov–Phillips regularization parameter via reproducing best invariant quadratic uniformly unbiased estimates (repro-BIQUUE). 2008, 82(2): 113–121

GNSS Remote Sensing at GFZ: Overview and Recent Results

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GNSS atmospheric remote sensing was successfully established during the last two decades and evolved into a major application for high precision GNSS. Globally distributed vertical profiles of refractivity, temperature and water vapour are derived from satellite based GNSS data (Radio Occultation, RO). Ground based measurements, provided by GNSS networks, allow for the derivation of vertically (IWV) or along the line-of-sight integrated water vapour (SWV). Another important GNSS remote sensing technique, the exploitation of Earth reflected signals (GNSS Reflectometry, GNSS-R) exhibits a huge potential for Earth Observation.
The status of the GNSS-RO experiments aboard the satellites GRACE-A, TerraSAR-X and TanDEM-X is reviewed. Examples of GNSS RO applications are given, as, e.g. climatological investigations of the global vertical temperature structure or the detection of ionospheric irregularities in the E-region. We also focus on ground based activities for GNSS water vapour monitoring. Observations of a global and regionally densified German network, with about 600 stations in total, are processed in near-real time to operationally provide IWV data. These data are assimilated into atmospheric models by several European weather centers. Current research activities are focused on the generation and meteorological application of GNSS based slant data, on real-time and multi-GNSS meteorology. In addition, climatological investigations are described to analyse long-term trends of the atmospheric water vapour over Germany but also as part of the Global Climate Observing System (GCOS) of the WMO (World Meteorological Organization).
Multipath data from standard GNSS receivers are used to derive information on soil moisture, vegetation and snow properties. We introduce selected research examples. We also review results from GNSS receivers aboard flight and ship platforms using the GNSS-R phase altimetry technique.

*G06-1-02
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A new baseline processing strategy for GNSS meteorology

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Though GNSS data processing has been significantly improved over years it is still commonly observed that tropospheric parameters (ZTD and gradients) contain many outliers. Detection and removal of outliers in GNSS time series is an important step before their use in meteorology and climatology. We show that outliers in double difference processing are often caused by defects in the baseline strategy. We elaborate and test a new baseline strategy which solves this problem and significantly reduces the number of outliers. One year of data is analyzed from a network of 136 GNSS stations. Three baselines strategies are inter-compared: 1) a strategy commonly used for positioning (e.g. determination of national reference frame) in which the pre-defined network is composed of a skeleton of reference stations to which secondary stations are connected in a star-like structure; 2) the widely-used "obs-max" strategy available in Bernese GNSS software (e.g. for processing of regional to global networks); and 3) our new baselines strategy.
It is shown that many outliers are due to data gaps at reference stations which cause disconnections of clusters of stations from the reference network. These outliers are common–mode biases due to the strong correlation between stations in short baselines. They can reach a few centimeters in ZTD and can be detected by a jump in formal errors. The magnitude and sign of the bias is impossible to predict, because it depends on different errors in the observations and on the geometry of the baselines. Several cases are illustrated. This defect is shown to strongly impact the 2 most widely used strategies. Our new strategy ensures that no station is disconnected from the main network and that all clusters include long baselines necessary to estimate absolute tropospheric parameters. This strategy might help to improve significantly the quality of GNSS tropospheric parameters estimated in national to regional networks for meteorology.

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Impact of advanced ZTD estimate method – Separation from site coordinates estimation –

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We introduce the new procedure to estimate zenith total delay (ZTD) to obtain GPS precipitable water (PWV) for the assimilation of the numerical weather models (NWM). In general, the major systematic error source of the ZTD estimation is the trade-off between the ZTD and the coordinate solutions usually simultaneously estimated in the GNSS analysis. In the analysis of the ZTD estimation, we fix the accurate site coordinates and exclude the trade-off systematic errors.
In the first step of the procedure, we estimate site coordinates as well as hourly ZTD, every four-hourly atmospheric gradient, and independent ambiguities of all of the GEONET network sites as well as the IGS fiducial sites applying the GAMIT program. In the second step, we estimate the accurate present-day site coordinates of the GEONET sites, estimating from the recent 30-days' time series of the site coordinates solutions applying the Kalman filtering of the GLOBK program, constraining the IGS fiducial site coordinates. Then in the final step of the procedure, we estimate every hourly ZTD and every four-hourly gradients of the GEONET sites fixing the site coordinates obtained in the second step.
To evaluate the advanced ZTD estimation, we compare the PWV values calculated from the three kind of ZTDs obtained by three different analysis procedures. We assimilate the PWVs to the CReSS NWM, and examine the impact of the PWVs in the heavy rain in the Southern Gifu Prefecture, Central Japan, on July 15 2010. Examining the wide area distribution of water vapor in the objective analysis, only the ZTDs obtained applying the procedure mentioned above (advanced ZTDs) shows the sharp contrast of the mixing ratio. coincides significantly The heavy rain phenomena calculated using the advanced ZTDs only significantly coincides with the observation.

*G06-1-04
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Main achievements of the Working Group 1 “Advanced GNSS Processing Techniques" of the COST Action ES1206: GNSS for Severe Weather and Climate (GNSS4SWEC)

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The COST Action ES1206 GNSS4SWEC addresses new and improved capabilities from developments in both the GNSS and meteorological communities. The synergy of all GNSS systems (GPS, GLONASS, Galileo and BeiDou) are used to develop advanced tropospheric products, exploiting the full potential of multi-GNSS water vapour estimates on a wide range of temporal and spatial scales, from real-time monitoring and forecasting of severe weather, to climate research. The Working Group 1 (Advanced GNSS processing techniques) deals with implementing and assessing new methods for GNSS tropospheric monitoring and precise positioning exploiting all modern GNSS constellations, signals, products etc. Besides other goals, WG1 coordinates development of advanced tropospheric products in support of weather numerical and non-numerical nowcasting.These are ultra-fast and high-resolution tropospheric products available in real time or in a sub-hourly fashion and parameters in support of monitoring an anisotropy of the troposphere, e.g. horizontal gradients and tropospheric slant path delays.
We give an overview of WG1 activities and focusing on achievements within Benchmark and Real-time Demonstration campaigns. For the Benchmark campaign a complex data set of GNSS observations and various meteorological data were collected for May-June 2013 which included severe weather events in central Europe. An initial processing of data sets from GNSS and numerical weather models (NWM) provided independently estimated reference parameters – ZTDs and tropospheric horizontal gradients. The Benchmark data set is used for development of an optimal strategy for real-time processing and a validation of tropospheric horizontal gradients and line-of-sight tropospheric slant total delays from GNSS, NWM-raytracing and Water Vapour Radiometer solutions. Real-time campaign is used to demonstrates products achieved in operational GNSS real-time analysis.

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Heterogeneity of residuals from GNSS and ray-traced tropospheric delays as an indicator of hydrometeors

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We attempt to indicate hydrometeors content along ray-path trajectories between ground-based receivers and respective GNSS satellites. Using tropospheric delays retrieved from GNSS data in Precise Point Positioning (PPP) and associated ray-traced delays in Numerical Weather Prediction (NWP) model, we are able to calculate residuals resulting from different processing approaches. When precise satellite orbits and clocks are applied, GNSS post-fit residuals carry the troposphere information except of multipath and residual antenna Phase Centre Variations (PCVs). After post-fit residuals are reduced by site-dependent systematic effect, they are introduced to GNSS-based delays increasing discrepancies with respect to ray-traced delays. Assuming the hydrometeor information in GNSS solution is correct, we expect the effect to be significant during severe weather events since ray-traced tropospheric delays exclude aerosols contributions. We conducted spatial and temporal correlation analysis of the slant delay residuals (GNSS minus ray-traced) with weather phenomena recorded during the COST ES1206 GNSS4SWEC benchmark period (May 5th - June 29th, 2013). We also discuss results that arise from different GNSS PPP slant delay estimation approaches related to coordinates constraining and inclusion of ZTD horizontal gradients.

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Analysis of systematic effects in slant total delay estimation with PPP

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Slant total delay (STD) of GNSS signal estimated during the PPP procedure is a sum of a priori slant hydrostatic delay, estimated wet delay, asymetry introduced by the estimated zenith total delay (ZTD) horizontal gradients and a post-fit residual reduced by the systematic (site-dependant) effect. The main systematic influence on STD is the multipath error. It can be determined from the long time series of post-fit residuals as their average value calculated in equal-area bins or calculated from the raw GNSS observables.
Paper presents the review and comparison of systematic effect maps (mainly multipath) obtained from PPP slant delay estimation post-fit residuals for a set of GNSS stations gathered in the COST ES1206 GNSS4SWEC benchmark database. We are presenting as well the systematic effect influence on estimated STD values through the results of comparison with STDs from WRF model raytracing.

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High-resolution troposphere models based on Numerical Weather Prediction for GNSS real-time Precise Point Positioning

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Tropospheric delay is highly correlated with the receiver clock and receiver height. To efficiently de-correlate these parameters in Precise Point Positioning (PPP), a change in constellation geometry is required. An alternative approach is to introduce the external high-quality regional tropospheric delay model to constrain tropospheric estimates. In this study, we present a high-resolution troposphere model based on Numerical Weather Prediction (NWP) model and Global Navigation Satellite Systems (GNSS) data, suitable to support PPP. We investigate the impact of different tropospheric models and mapping functions on the position accuracy and convergence time. We propose a routine to constrain the tropospheric estimates, which we implemented in the in-house developed real-time PPP software. We take advantage of the spatial high-resolution NWP Weather Research and Forecasting (WRF) model to reconstruct troposphere delay from WRF model and near real-time GNSS data combined by the least-squares collocation technique. We also present mapping functions calculated from WRF model using the ray-tracing technique. We compare commonly used troposphere models such as UNB3m or VMF1-FC and the high-resolution GNSS/WRF-based troposphere model with the reference EUREF Permanent Network (EPN) data on 14 Polish stations during three weeks of different tropospheric conditions: calm, standard and severe. The application of the high-resolution model results in the best agreement with the official EPN coordinates. In both static and kinematic mode this approach results in average reduction of 3D bias by 20 and 10 mm respectively. The application of high-resolution tropospheric model also shortens the convergence time by 13% for horizontal components and 20% for vertical component compared to the standard models.

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Optimum stochastic modeling for GNSS tropospheric delay estimation in real-time

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In GNSS data processing, the station height, receiver clock and tropospheric delay (ZTD) are highly correlated to each other. Although the zenith hydrostatic delay of the troposphere can be provided with sufficient accuracy, zenith wet delay (ZWD) has to be estimated, which is usually done in a random walk process. Since ZWD temporal variation depends on the water vapor content in the atmosphere, it seems to be reasonable that ZWD constraints in GNSS processing should be geographically and/or time dependent. Rather than performin a prior empirical testing for each station, we propose to take benefit from numerical weather prediction (NWP) models to define optimum random walk process noise. In the first approach, we used archived VMF1-G data to calculate a grid of yearly means of the difference of ZWD between two consecutive epochs divided by the root square of the time lapsed, which can be considered as a random walk process noise. Alternatively, we used the Global Forecast System NWP model from National Centres for Environmental Prediction to calculate random walk process noise dynamically in real-time, by performing ray-tracing through the two shortest available forecasts.
We performed two representative experimental campaigns with 20 globally distributed International GNSS Service (IGS) stations and compared real-time ZTD estimates with the official ZTD product from the IGS. We have shown that a single random walk processing noise (RWPN) value should not be applied globally to all stations, because it may lead to significant degradation of solution quality. With RWPN yearly grid we were able to reconstruct the wet RWPN value obtained from empirical testing with a mean error of 1mm/sqrt(h). A superior result was obtained with dynamical NWP-based apporach, in which we obtained an improvement of up to 10% in accuracy of the ZTD estimates compared to any uniformly fixed random walk process noise applied for all stations.

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Impact assessment of regional versus global Numerical Weather Model–derived tropospheric corrections for GPS and VLBI

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Mapping functions based on Numerical Weather Models (NWM) have been developed in the recent years to model tropospheric delay in Global Positioning System (GPS) and Very Long Baseline Interferometry (VLBI).Their limited accuracy however, requires the estimation of residual tropospheric delay for results of high accuracy.
Correlation between the tropospheric delay, the receiver clock offset and the station height prolongs the time required for the solution to converge and impacts directly the accuracy of the results. Although observation in low elevation angles, help the parameters to de-correlate, they amplify the noise, are not always adequate and it is a highly demanding prerequisite for real-time applications.
In this study, we applied tropospheric corrections proceeding from high resolution NWM in Precise Point Positioning (PPP), in an attempt to acquire rapid and accurate positioning results, particularly useful for kinematic applications, positioning in non-standard weather conditions and obstructed environment, where estimation of tropospheric delay/height/clock offset is ambiguous.
Although regional NWM have outperformed standard atmosphere parameters and global models, it is the first time they were compared against other NWM-derived corrections; such as the state-of-art Vienna Mapping Function 1 (VMF1) parameters.
To eliminate processing systematic effects, a consistent VLBI solution was generated.
The results were assessed in terms of their formal errors, convergence time, station coordinate and baseline repeatability respectively, for the PPP and VLBI analysis.
Results shown minimal improvement in convergence time in “non-demanding" conditions, but “cm" height differences in kinematic mode and cases of tropospheric disturbances for specific sites. The quality of the corrections and the filter a-priori variance, are barometrical for the final solution.

A Study of Severe Storm Monitoring and Prediction using High Spatio-temporal GNSS Water Vapor Information Retrieved with RTKLIB and MADOCA

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Water vapor plays a significant role on development of hazardous cumulus convection. Water vapor monitoring with high temporal and spatial resolution is indispensable for both predicting and monitoring of such disastrous weather phenomenon. In Japan, a nationwide dense continuous ground based GNSS network named GEONET (http://www.gsi.go.jp/ENGLISH/page_e30030.html) has also been utilized as a continuous water vapor monitoring network by the Japan Meteorological Agency since 2009.

In order to capture finer water vapor variation, we have been developing two new applications, as (1) GNSS slant-path delay (SPD) utilization to detect strong horizontal water vapor gradient within several kilometer which associated with convective activities [1][2], and (2) observation system of water vapor over the ocean using GNSS receivers equipped on top of floating buoys and vessels [3].

One of the most important point of these application is its real-time availability. We have tested "MADOCA (Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis)" real-time ephemerides (https://ssl.tksc.jaxa.jp/madoca/public/public_index_en.html) applied to the program package for GNSS positioning "RTKLIB (http://www.rtklib.com/)" version 2.4.2 (patch 11). The results so far show great potential of RTKLIB with MADOCA for severe weather prediction and monitoring.

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Integrated water vapor trends from VLBI analysis, and their validation with GNSS and numerical weather models

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We assess the impact of different modeling and parametrization of the propagation delay in the electrically neutral atmosphere on the estimates of geodetic very long baseline interferometry (VLBI). Erroneous meteorological observations applied to mitigate the tropospheric delay, as well as unsuitable constraints imposed on the a priori gradients, especially in VLBI sessions with poor geometry, corrupt the data analysis and thus distort the VLBI estimates. Hence, these issues affect the long-term integrated water vapor (IWV) trends estimated from these results. The explicit purpose of this work is to address the impact of the meteorological data source, and of the a priori non-hydrostatic delays and horizontal gradients employed in the VLBI analysis, on the estimated IWV trends. We explore the effect of employing pressure and temperature from (i) homogenized in situ records, (ii) the model level data of ERA interim and (iii) an own empirical model in the style of GPT2w with enhanced parametrization, employing the latter data set as input. Moreover, we apply non-hydrostatic delays and gradients stemming from (i) a GNSS reprocessing at German Research Centre for Geosciences Potsdam, after accounting for troposphere ties and (ii) direct ray-tracing through ERA interim. For the evaluation we modified the least-squares module of the VieVS@GFZ VLBI software to produce two series of solutions. We study the noise characteristics of the non-hydrostatic delays and horizontal gradients estimated from our VLBI analysis as well as from GNSS and ray-tracing. We modified the Theil-Sen estimator appropriately to robustly deduce IWV trends from VLBI and GNSS observations, as well as ray-tracing and direct numerical integration in ERA interim.

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Tropospheric ties for inter-technique comparisons and combinations

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Tropospheric parameters are necessarily part of the adjustment process within space geodetic high-precision geodetic processing when using GNSS, DORIS or VLBI data. The intra-/inter-technique comparisons of tropospheric parameters, resulting as by-products of the analyses, provide a useful feedback for the evaluation of the state-of-the-art models and strategies in the reprocessing. The development of combining space geodetic techniques at an observation level suggests external computation of tropospheric ties in order to estimate a single tropospheric correction for two or more collocated stations of different techniques.

The tropospheric ties are optimally separated into two components - zenith dry and wet delays. Several models have been used in the past for calculating tropospheric ties for inter-technique comparison of tropospheric parameters. Recently, we have developed a new method particularly improving vertical scaling of the wet component. Different strategies require different external meteorological data or other specific tropospheric parameters fitted specifically for vertical scaling. The tropospheric ties may be calculated using actual numerical weather data field. Both the accuracy and the simplicity of calculating tropospheric ties will play a key role in a practical implementation of tropospheric ties in future inter-technique comparison and combination activities.

We evaluated different strategies for calculating or approximating tropospheric ties within two basic scenarios: a) using numerical weather reanalysis data fields (ERA-Interim) for an assessment of optimal strategy for the vertical scaling of dry and wet tropospheric components independently, b) assessing the impact of tropospheric ties in comparison of GNSS and radiosonde tropospheric parameters, and c) evaluating tropospheric ties specifically for GNSS, VLBI and selected DORIS collocated stations in order to assess the impact of tropospheric ties in inter-technique comparison.

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Detection of both icecap and crustal deformation associated with the 2014-2015 Bardarbunga rifting episode

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The 2014-2015 Bardarbunga rifting episode is one of the largest event in Iceland. Previous studies have already reported that the earthquake swarm migrated from Bardarbunga to Holhraun where the fissure eruptions occurred at northern edge of Vatnajokull icecap. There were few ground-based GPS observation points near the epicenters of the swarm. While the nearby crustal deformation associated with the episode have also been detected by using satellite InSAR-data, phase decorrelation problems have hampered detecting the icecap deformation during the rifting episode. Although the icecap has been known to flow steadily, one of our motivations is to see if the rifting episode affected the flow speed of ice in light of the well-known Jokulhlaups event by subglacial eruption. Moreover, phase-based InSAR measurement does not allow for the detailed measurement of the subsidence over the graben, which is indispensable to constrain the volume and geometry of intruded dike.

In this study, we processed COSMO-SkyMed images to simultaneously detect both the flow signals on the icecap and the crustal deformation associated with the rifting event. The offset tracking data derived from COSMO-SkyMed images showed the displacement signals that consist of both the crustal deformation over land and the icecap flow. Two displacement discontinuities were detected not only on the land but also on the icecap, while we could not capture the entire image of the both deformations due to the limited SAR image coverage. The 3D displacements revealed a graben structure with over 8 m subsidence at the graben floor. At the graben floor, approximately 1 m of the rift-parallel motion which caused by the dog-bone seismicity was detected. Using these observation results, we will estimate the dike intrusion model and discuss the possible interaction between the ice and the crustal deformation during the 2014-2015 Bardarbunga rifting episode.

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Taiwan/TriG Radio Occultation Process System (TROPS)

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ABSTRACT
Global Positioning System (GPS) Radio Occultation (RO) technique has been used to investigate the Earth's atmosphere since 1990. In 2006, Taiwan has launched six low Earth orbit (LEO) satellites as a RO constellation mission, named FORMOSAT-3 /COSMIC (F-3/C). F-3/C mission can release 1500-2500 data sets per day for both neutral atmosphere and ionosphere. With the advent of Global Navigation Satellite System (GNSS) in ten years and FORMOSAT-7/COSMIC-2 (F-7/C-2) mission, 12 LEO satellites are planned to be launched and deployed in two clusters of 6-satellites into the designated low and high inclination orbits in 2017 and 2019 (TBD), respectively. The amount of RO data set will increase to about 8000 set per day with the using of GNSS TriG (GPS, Glonass, Galileo) receivers. The first phase of F-7 mission is designed to low inclination (24 deg) orbit to improve the ability of server weather forecasting, like typhoon and monsoon rainfall around tropical region. The second is high inclination (72 deg) for global distribution. This report will introduce the constellation of F-7/C-2 mission, the distribution of RO profiles, and the status of FORMOSAT-7 Taiwan/Trig RO process System (TROPS) including Determination(POD), ionospheric and atmospheric data process.

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Global and regional high resolution VTEC Representations using B-Splines and Kalman filtering

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The project OPTIMAP is a joint initiative of the Bundeswehr Geoinformation Centre (BGIC), the German Space Situational Awareness Centre (GSSAC), the German Geodetic Research Institute of the Technical University of Munich (DGFI-TUM) and the Institute for Astrophysics at the University of Goettingen (IAG). The main goal of the project is the development of an operational tool for ionospheric mapping and prediction. The tool will consider all available observation techniques (GNSS, satellite altimetry, radio occultations and DORIS) which are sensitive for the ionosphere and provide global and regional VTEC products with a high spatial and spectral resolution within a two-level model (TLM).

Since the ionospheric observations from space-geodetic missions are distributed rather unevenly over the globe, an appropriate modeling approach has to be developed. Our approach is based on a two-level strategy with a global modeling part as the first and a regional modeling part as the second level. To be more specific, the global VTEC model contains moderate regional and spectral resolution, while in areas with a dense measurement distribution, a regional VTEC model with a higher resolution is set up.

The global VTEC model part is based on a series expansion in terms of polynomial B-Splines in latitude direction and trigonometric B-Splines in longitude direction whereas the regional model part is set up by polynomial B-splines for both directions.

In terms to avoid dependencies between the global and the regional models a data selection by means of a "thinning out" procedure, based on station positions, is applied. The two selected subsets of observations are exploited within multiple Kalman filtering processes which are running in parallel mode in order to estimate the unknown B-spline series coefficients. Additional technique-dependent unknowns such as the GNSS Differential Code Biases (DCBs) are considered. In this contribution we will present the first numerical results.

The optimal regularization (alpha-weighted BLE via A-optimal design) and its application in GNSS-based ionospheric tomography

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In this talk the optimal uniform Tykhonov-Phillips regularization (alpha-weighted BLE) by A-optimal design (minimizing the trace of the Mean Square Error matrix MSE) is reviewed. The determination of optimal regularization parameter via A-optimal design is introduced and its comparison with the results derived by numerical heuristic methods, such as by means of L-Curve, GCV and ridge trace is also performed. In which the A-optimal design regularization parameter has been shown to have minimum trace of MSE and its calculation has better efficiency.

In the reconstruction of ionospheric tomography based on the GNSS observations, geometrical limitations (no horizontal ray path, incomplete viewing angles, a limited number of receiving stations, etc.) of the data acquisition system cause the available data insufficient for ideal reconstruction tomography, which makes ionospheric tomographic reconstruction an ill-posed problem. In order to overcome the non-uniqueness of ionospheric tomographic reconstruction, many algorithms have been developed. For example, several kind of regularization algorithms have been applied in solving this kind of ill-posed problem. In these applications how to determinate an optimal regularization parameter is remaining an open problem. As a case study here the A-optimal design regularization will be implemented in solving the ill-posed problem of GNSS-based ionospheric tomographic reconstruction. The reconstruction results will be also analyzed and discussed in the sense of optimal and efficient aspects.

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Contributions to real time and near real time Ionosphere Monitoring by IAG's RTIM-WG

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The status and the research carried out within the International Association of Geodesy (IAG) Real Time Ionosphere Monitoring Working Group (RTIM-WG), which is part of IAG's Sub-Commission 4.3 Atmosphere Remote Sensing, will be presented.
Of particular interest within the research community is the analysis of St. Patrick's Day 2015 geomagnetic storm, which will be extended to account for correlations among the multiple independent real time and near real time (global or regional) ionospheric approaches. In this regard, ionospheric parameters, such as Total Electron Content (TEC), foF2, hmF2, B0, B1 and the ionospheric disturbance W-index, will be considered thanks to the complementary expertise of the WG members.
In addition, the analysis of real time and near real time VTEC Global Ionospheric Maps (GIMs) is another major goal within the team. In this context, the comprehensive study carried out in Roma-Dollase 2016 (D. Roma-Dollase, M. Hernandez-Pajares, A. Garcia-Rigo, D. Laurichesse, M. Schmidt, E. Erdogan, Y. Yuan, Zishen Li, J. Ma. Gomez-Cama and A. Krankowski, Real Time Global Ionospheric Maps: a low latency alternative to traditional GIMs. Beacon Satellite Symposium 2016, June 27 2016, Trieste, Italy) will be extended based on existing real time and near real time ionospheric VTEC models within the WG, supporting the IONEX format. In this context, validation based on external data from JASON dual-frequency altimeter will be performed.
Last but not least, experiences within the WG on dissemination and format of GIMs in order to properly support real time usage will be outlined to promote discussion on this open topic.

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S4 index observations and global morphology of ionospheric scintillations using FS3/COSMIC GPS radio occultation data

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We report on the FormoSat-3/ Constellation Observing System for Meteorology, Ionosphere and Climate (FS3/COSMIC) limb-viewing observations of GPS L-band scintillations since mid-2006 and propose to study global F-layer irregularity morphology. The FS3/COSMIC has generally performed >1000 ionospheric radio occultation (RO) observations per day. We reprocess 1-Hz amplitude data and obtain complete limb-viewing profiles of the undersampling-S4 scintillation index from about 80% of the RO observations. There are a few percent of FS3/COSMIC RO observations having >0.09 undersampling S4max values on average. However, seven identified areas Central Pacific Area (-20˜20 deg dip latitude, 160 deg E˜130 deg W), South American Area (-20˜20 deg dip latitude, 100 deg W˜30 deg W), African Area (-20˜20 deg dip latitude, 30 deg W˜50 deg E), European Area (30˜55 deg N, 0˜55 deg E), Japan Sea Area (35˜55 deg N, 120˜150 deg E), Arctic Area (>65 deg dip latitude) and Antarctic Area (<-65 deg dip latitude) have been designated to have a much higher percentage of strong limb-viewing L-band scintillations. During these years in most of the last sunspot cycle from mid-2006 to the end 2014, the scintillation climatology, namely, its variations with each identified area, season, local time, magnetic activity and solar activity have been documented.

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3-D Tomography of Daytime Mid-latitude Sporadic-E from GNSS Data

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We study ionospheric irregularities caused by daytime midlatitude sporadic-E (Es) in Japan using 3-D (three-dimensional) ionospheric tomography. Es is a thin layer of unusually high ionization that appears at the altitude of ~100 km. In previous studies, we imaged the Es patches on 2-D maps over Japan (Maeda & Heki, 2014 Radio Sci.; 2015 EPS) using changes in the ionospheric Total Electron Content (TEC) observed with Japanese GNSS receiver array, GEONET. They found that Es usually show frontal structure extending hundreds of kilometers predominantly in east-west.

Using the slant TEC residuals as an input, we estimate the electron density anomalies within >2000 small blocks with dimensions of a few tens of kilometers over a region of 300 x 500 km. We applyed a certain continuity constraint to stabilize the solution. We considered the distribution of GNSS line-of-sights to know which area will be properly resolved, and performed checkerboard resolution tests with synthesized data before using the actual observation data.

We select two examples of clear Es irregularities, i.e. Case 1 over the Kanto District at ~8 UT on 21 May 2010, and Case 2 over the Kyushu District at ~4 UT on 22 May 2010. They are first studied by Maeda & Heki (2014) and Maeda & Heki (2015), respectively. We confirmed that the positive electron density anomalies showed frontal shapes extending east-west at the E region altitude. In the first case, Es patch slowly moved southward, and it moved rather rapidly northward in the second case. One interesting feature in their 3-D structures is that positive anomalies expand upward and northward in Case 1, and upward and southward in Case 2. The results suggest that the extension direction of the upward continuation of Es patches might be controlled by their horizontal drift directions.

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Dispersive and Non-dispersive Components in the L-band InSAR Data Associated with Sporadic-E and Heavy Rain Episodes

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In contrast to GNSS, SAR imaging is based on a single carrier frequency, and thus no operational ionospheric corrections have been performed in the interferometric SAR (InSAR) data analyses. Recently, Gomba et al (2016) detailed the processing strategy of split-spectrum method (SSM) for InSAR, which splits the finite bandwidth of the range spectrum and virtually allows for dual-frequency measurements. We apply the SSM to the L-band ALOS1/2 InSAR data to examine the contributions of dispersive and non-dispersive components. Maeda et al (2016) succeeded in detecting the sporadic-E (Es) signals in both GNSS/TEC and ALOS/PALSAR InSAR data. Meanwhile, Kinoshita and Furuya (2017) detected phase anomaly in ALOS/PALSAR InSAR data associated with heavy rain over Niigata area, Japan. In this paper, we apply the SSM to the L-band InSAR data that detected both Es and heavy rain episodes. Originally, we expected no anomalies in non-dispersive phases for Es and in dispersive phases for heavy rain. To our surprise, however, we notice the presence of phase anomalies in both dispersive phase in heavy rain and non-dispersive phase in Es. We discuss its geophysical implications.

*G06-4-04
IAG Symposium / IAG04. Positioning and Applications / G06. Geodetic remote sensing

Remote sensing of ionospheric TEC using GNSS observations in relation to space weather events and seismic activity in Bosnia and Herzegovina

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Radio signals on their way from Global Navigation Satellite Systems (GNSS) to receiver on the Earth pass through various layers of atmosphere where ionosphere has major influence on their propagation, which affects accuracy of positioning and navigation. Monitoring of ionosphere above Bosnia and Herzegovina was conducted using European Permanent Network (EPN) station SRJV in Sarajevo by investigating total electrons content (TEC) variability with possible causes of its sudden variations, such as due to space weather and seismic activities. Day to day variability, seasonal variations, solar activity dependence and long term TEC trends were investigated for three years (2014 – 2016) from solar maximum to its next minimum in the solar cycle 24. For statistical analysis lower and upper bounds were determined by 15-day medians prior and after TEC anomaly ± 2*standard deviation. Results were combined with data of x-ray flux from Geostationary Operational Environmental Satellites, magnetic activity indices (Kp Ap Dst), observations of sudden ionospheric disturbances using SuperSID monitor. Transition of solar cycle from its maximum to its minimum is evident in decreasing trend of TEC from 2014 to 2017. Although some patterns of TEC variability could be observed, sudden anomalies caused major disturbances in ionosphere mostly due to space weather. The strongest geomagnetic storm (Kpmax=8-, Ap=108) in current solar cycle (17/03/2015) increased TEC values for near 60% from monthly median and than decreased to 40% in following days. Anomalous TECs were investigated for seismic activity of medium intensity (4<M<5). TEC anomalies prior earthquakes were mainly caused by gap in data and effects of space weather, but the rest of anomalies might be connected to seismic activities, such as negative anomalies to 5 TECU under lower bound observed on the day before and few days after the earthquake with epicenter 13km far from EPN station SRJV, which requires further investigations.

*G06-4-05
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Assessment and comparisons of ionospheric vertical total electron content products

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Accurate modelling of the ionosphere is crucial for GNSS-based applications in positioning and navigation to mitigate the effect of ionospheric disturbances. Large volumes of GNSS data, which are acquired from continuously operating terrestrial GNSS receivers and distributed worldwide, pave the way of monitoring the Vertical Total Electron Content (VTEC) of the ionosphere with an increasing accuracy as time goes by. In this context, many analysis centres are v providing VTEC products with different latencies (e.g. real-time, hourly, daily) and quality as well as they spent effort to improve their models.

The UPC-IonSAT group generates global VTECs maps both in real-time and in post-processing mode using its Tomographic Model of the Ionosphere electron content (TOMION) software. This software works as an assimilative model of GPS data to create a global 2-layer voxel tomographic representation solved with a Kalman filter.

The VTEC model of DGFI-TUM is based on tensor products of trigonometric B-spline functions in longitude and polynomial B-spline functions in latitude for a global representation. The unknown parameters of the model are sequentially estimated by assimilating GNSS observations using a Kalman filter.

In this study, the performance of the VTEC maps, particularly derived from UPC and DGFI-TUM, is assessed, using e.g. the differenced STEC analysis method and Jason-2 altimetry comparisons. We also compare our results with other available products, e.g. IGS VTEC maps. Furthermore recent model improvements are presented.

*G06-5-02
IAG Symposium / IAG04. Positioning and Applications / G06. Geodetic remote sens ing

IAG/GGOS inter-comparison campaign on SNR-based GNSS reflectometry for sea level monitoring

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A joint working group (JWG 4.3.9) on GNSS reflectometry (GNSS-R) was established at the end of 2015 under the auspices of the International Association of Geodesy (IAG) and the Global Geodetic Observing System (GGOS). Its goal is to foster the adoption of GNSS-R corrections (e.g., hydrological loading) in geodetic positioning as well as the generation of environmental parameters (e.g., soil moisture and coastal sea level) based on GNSS-R using conventional geodetic instrumentation. Of particular interest are sea level estimates using existing GNSS networks by means of signal-to-noise ratio (SNR) analysis. This application has the potential to become a GGOS data product and an IAG data service in the near future. JWG 4.3.9 initiated an inter-comparison campaign on SNR-based GNSS-R for sea level monitoring at the end of 2016. Its purpose is to assess retrieval solutions from independent research groups under comparable conditions. One year of RINEX files with GNSS measurements collected at the Onsala Space Observatory, Sweden, were made available to JWG 4.3.9 members. More than half participated submitting single-signal solutions (GPS L1 C/A) as well as a dual-frequency (L1/L2) and dual-constellation (GPS/GLONASS) multi-signal solutions. In general, we found good agreement between the co-located tide gauge record and SNR-based GNSS-R retrievals from different groups. Most correlation coefficients exceed 0.9 and standard deviations are at sub-decimeter level, with some solutions approaching 0.99 and few-cm, respectively. Systematic effects and/or dependency on meteorological conditions have been revealed and are subject of further discussion within JWG 4.3.9.

*G06-5-03
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Sea level retrieval based on fitting model of GNSS SNR observations

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Long-term water level monitoring in coastal regions is important to understand how the local sea level is changing and affects the human life. This paper presents a new altimetric method for retrieving sea surface heights by global navigation satellite signals reflected over the ocean surface. It uses SNR observations from a single geodetic receiver. A detrended SNR fitting model depends on different impact factors of SNR measurements is proposed. The fitting model searching process includes two steps: the coarse parameters of the detrended SNR model for the whole elevation period of different satellites are searched based on optimization method firstly. Then, the fine model parameters for small temporal samples are refined based on the estimated coarse parameters. Ground-based sea level measurements that was conducted at the Onsala Space Observatory from July 1, 2015 to June 30, 2016 demonstrate, that altimetric information about the reflecting water surface can be obtained with a Root Mean Square Error of 9.29 cm with respect to a reference tide gauge dataset. The sea surface changes, derived from our field experiment and the reference tide gauge, are highly correlated with a correlation coefficient of 0.93. Experimental results of the SNR measurements show the proposed method can perform much higher temporal resolution and have higher accuracy when compared to the previously spectral methods.

*G06-5-04
IAG Symposium / IAG04. Positioning and Applications / G06. Geodetic remote sens ing

Observation of sea surface heights from moving ships based on analysis of GNSS-SNR data

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Current studies investigate the possibilities to combine satellite altimetry and tide gauge readings with GNSS-based observations from moving ships to derive precise information of the sea surface height (SSH). The latter method requires determining the variable distance between the GNSS antenna and the undisturbed water surface. Commonly the distance is calculated based on hydrostatic and hydrodynamic data. Since some of the necessary corrections are not always available or not easy to derive (draft changes due to fuel consumption or ship squat), it would be desirable to connect the GNSS antenna and the sea surface by direct and continuous observations.

It is well-know that GNSS-SNR data can be utilized to derive water surface heights. Up to now, existing inversion techniques were only used for the analysis of SNR observations from static GNSS antennas. If these techniques could be applied also to observations from moving ships, the resulting reflector height could be used together with GNSS -derived antenna heights to directly observe the ellipsoidal height of the water surface around the ship without the need of dynamic corrections.

To assure that the used SNR observations are not influenced by the wave system of the ship only data from low elevation angles should be analysed. The movements of the ship can be calculated from the observations of at least three GNSS antennas aboard the ship and will be used to correct for the short-periodic variations of reflector heights in the inversion step. Hence, the static reflector height together with a long-term variation due to draft change and squat effect can be modelled as 2D time depending function.

The inversion of the SNR data is carried out by global optimization based on interval analysis. This method will be applied to a data set from a ship cruise in the North Sea. The results from this experiment will be presented and future applications will be discussed.

*G06-5-05
IAG Symposium / IAG04. Positioning and Applications / G06. Geodetic remote sens ing

Wind Direction Retrieval in Airborne Experiments of a GNSS-R Receiver

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The GNSS reflected signals have been proposed for the remote sensing of sea surface altimetry, ocean wind speed, salinity, soil moisture. A GNSS reflection receiver provides the delay-Doppler map (DDM) as the raw measurement for the retrieval of remote sensing variables. Indeed, the spreading and geometry of the DDM is related to geophysical property of ocean surface. In this paper, the experimental and retrieval results by using a GNSS reflectometry (GNSS-R) receiver are described. The GNSS-R receiver is an indigenous design that is capable of processing reflected GNSS signals and generating the DDM in real time. Two airborne experiment data sets are processed for the retrieval of wind direction. The retrieval results are compared with the measurement result on buoys operated by the Central Weather Bureau of Taiwan. In addition, different retrieval methods are discussed.

*G06-5-06
IAG Symposium / IAG04. Positioning and Applications / G06. Geodetic remote sens ing

GNSS Reflectometry onboard the International Space Station with GEROS-ISS: Review of activities and current status

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GEROS-ISS is an innovative ISS experiment of the European Space Agency (ESA) primarily focused on exploiting reflected signals of opportunity from Global Navigation Satellite Systems (GNSS) at L-band to measure key parameters of ocean surfaces.
The primary mission objectives are: (1) to measure the altimetric sea surface height of the ocean using reflected GNSS signals and (2) to retrieve scalar ocean surface mean square slope (MSS), which is related to sea roughness, wind speed and direction.
Secondary mission objectives are related to further explore the potential of GNSS radio occultation data for global atmospheric sounding and to assess the potential of GNSS scatterometry for land applications.
Two competitive industrial phase A studies were completed in 2016, complemented by the international scientific study GARCA (GNSS-R – Assessment of Requirements and Consolidation of Retrieval Algorithms) to develop an End2End Simulator for the preparation of the GEROS-Mission and to perform Observing-System Simulation Experiments (OSSE) to assess the oceanographic significance of the expected GEROS-ISS measurements. In parallel to these studies dedicated flight campaigns were carried out to monitor the sea surface height of the Baltic Sea around Helsinki, Finland utilizing the interferometric GNSS-Reflectometry approach, which is planned to be implemented for GEROS.
GEROS was originally foreseen to be launched in 2019. Following the Phase A industrial contracts and the parallel scientific study, ESA is now leading a mission reduction exercise aimed at bringing its cost significantly down while keeping the most essential scientific objectives. We review the activities related to the GEROS-ISS experiment and inform on the recent mission status.

*G06-P-01
IAG Symposium / IAG04. Positioning and Applications / G06. Geodetic remote sensing

Assessing Precise Point Positioning Derived Zenith Total Delays Using the NIGNET

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Global Navigation Satellite Systems (GNSS) is increasingly being used worldwide in operational meteorology with the estimation of parameters such as zenith total delay (ZTD). Due to its continuous evolution, precise point positioning (PPP) has become an increasingly used technique for estimating ZTD from GNSS data. Many nations utilize dedicated GNSS receiver networks as continuously operating reference stations (CORS) for operational weather and climate services. The focus of this research is to assess the quality of PPP derived ZTDs using data collected by the Nigerian GNSS Reference Network (NIGNET) and a local and nearby International GNSS Service (IGS) station. NIGNET is a network of fourteen stations equipped with GPS and GLONASS dual frequency capable receivers. Data collected from 1st January 2011 to 9th November 2016 is used in the assessment. The estimates are compared with ray-traced estimates from the global Numerical Weather Model (NWM) of the National Centre for Environmental Prediction (NCEP), and estimates from the IGS final troposphere product. A time series analysis is performed to access the level of agreement of the products and identify possible systematic effects arising from the different techniques. Results indicate a 3 cm root mean square value of the differences, and that the variation exhibited by the PPP ZTD estimates correlates with known annual weather patterns across the country.

Calibration of empirical thermospheric models by using laser observations to near-Earth orbiting spherical satellites

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The thermosphere causes by far the largest non-gravitational perturbing acceleration of near-Earth orbiting satellites. Especially between 80 km and 600 km, the thermospheric density distribution and variations are required to accurately model this force. So far, mainly accelerometers onboard of satellites are used to measure the thermospheric density. However, such type of satellite is usually of complex shape and any error or miss-modelling of the satellite drag coefficients will directly propagate into the derived thermospheric density values.

At GFZ, an empirical model of the thermospheric mass density has been developed by using 9 years of CHAMP observations. The model is based on seven `key' parameters, namely height, solar flux, season, magnetic local time, geographic latitude, and magnetic activity.

A completely different approach is to use satellite laser ranging (SLR) measurements to satellites equipped with retro-reflectors to determine the most accurate satellite orbit. These measurements are sensitive to small perturbations acting on the satellite. In order to minimize the error induced by wrong satellite macro-models, we use ranging observations to satellites with a simple spherical shape. Therefore, the derived thermospheric density values can be seen as `absolute' density values.

In this study, we use SLR observations at least to the four ANDE satellites with altitudes between 350 km and 400 km to calibrate the empirical model developed at GFZ. The main features of the GFZ model are then compared to standard thermospheric models for different solar activity conditions.

*G06-P-03
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Impact of heat island effect on rainfall patterns under global warming: case study of Taipei City

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Sustained global development with the environmental issues have been repeatedly discussed and attention, while the Taipei region is also under the influence of climate change. In the past, it is known that there are severe heat island effects in the urbanized area of Taipei, and the hydrological change is caused by temperature change. The city continues to develop, so for the suburbs to carry out comprehensive weather detection and early warning is a matter of urgency. In this study, we observed the influence of heat island effect on the temperature, Precipitable Water Vapor (PWV) and rainfall in the suburbs. According to the results, the study confirmed that the urban area and the urban area have a rising trend during the period from 2006 to 2014, which is about 0.7 degree higher than that in the suburbs. The temperature in the suburbs decreases by 1.1 degree, of the decline is greater than the urban areas. The average PWV increased about 6.7 mm, the cumulative rainfall also increased about 54.7 mm. The other two high-temperature areas are gathered in the development zone, and in the northern mountain area presents a low temperature, heat island effect occurs obviously. Moreover, the rainfall is largest in the mountainous areas of the southern region in summer. While the winter due to wind direction, the rainfall falls in the northeastern region of the windward side. The results show that there is a significant urban heat island effect in the Taipei region, and the overall increase in the amount of PWV increases with the global warming and more rain falls in the urban area. In the face of future urban areas with more flooded conditions due to climate change, we need to strengthen the attention and planning of hardware for disaster prevention and flood prevention in urban areas to avoid irreparable disasters and losses.

*G06-P-04
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Ray-traced radio occultation profiles during tropical cyclones

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We used Global Forecast System (GFS) model as an environment to propagate microwave signal along occultation plane between GNSS satellite and low-Earth orbiter in order to assess ray-traced radio occultation atmospheric products. We restored 2-dimensional structure of bending angle and associated excess phase by means of geometry optics in non-spherically symmetric atmosphere neglecting out-of-plane components. Since the spherical symmetry assumption is commonly applied for retrieval of radio occultation profiles, we also considered the GFS refractivity above tangent point to be consistent with medium along propagation paths. The Abel transform is used to prove correct simulations. Above troposphere, where strong horizontal gradients usually are not observed, we were able to estimate signal amplitude under geometry optics. However, tropospheric signal to noise ratio needs to be resolved in wave optics due to multipath effect based on simulated bending angle profiles. The radio occultation data provided by COSMIC Data Analysis and Archive Center (CDAAC) in atmPrf and wetPrf products were considered as an additional source of reference for bending angle as well as atmPhs containing amplitude and phase data. To demonstrate capability of the ray-tracer, simulations were conducted under severe weather conditions on the example of tropical cyclones that passed through Taiwan in 2016. In such events, significant horizontal irregularities can be observed, hence we calculated and analyzed residuals between spherically symmetric and asymmetric ray-traced parameters together with amplitude variations.

*G06-P-05
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Regional Precipitation Prediction Based On Tropospheric Gradients and Delay Time Series

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Changes of temperature and humidity in the neutral atmosphere cause variations in tropospheric path delays and tropospheric gradients. Thus, time series of GNSS-based tropospheric parameters provide information about spatial and temporal variations of water vapour in the atmosphere and, therefore, can contribute to the forecast of regional precipitation events.
In a recently finalized master thesis at TU Wien the information content of tropospheric parameters for weather prediction was investigated. Two characteristics in ZWD and gradient time series can be anticipated in case of an approaching weather front. First, an induced asymmetry in tropospheric delays results in both, an increased magnitude of the gradient and in gradients pointing towards the weather front. Second, an increase in ZWD reflects the increased water vapour concentration right before a precipitation event. To investigate these characteristics exemplary test events were processed. Therefore, ZWD and gradient time series at selected GNSS reference stations were compared to precipitation data. All required meteorological data was provided by the Central Institution for Meteorology and Geodynamics (ZAMG).
It can be deduced, that GNSS-based tropospheric parameters show high potential for predicting precipitation events. The sequence of the anticipated increase in ZWD at each GNSS station indicates the orientation of the air mass boundary. Furthermore, the magnitude of ZWD increase at each station suggests, whether the station is affected by the precipitation event or not. Gradients rather indicate the direction of movement of an approaching weather front. Additionally our investigations have shown, that gradients are able to capture the characteristics of an approaching weather front twenty to thirty hours before the precipitation event, which allows a first indication well in advance.

*G05-P-06
IAG Symposium / IAG04. Positioning and Applications / G05. Multi-signal positio ning: Theory and applications

Multiplicative random error models: Parameter estimation and error analysis

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Conventional geodetic adjustment theory has been almost always developed on the linear and/or linearized model of measurements. The most important feature of these conventional adjustment methods and theory are that the random errors of measurements are added to the functional models. In other words, the sizes or magnitudes of random errors are independent of the true values of measured quantities. However, in geodetic practice, we know that this assumption is not necessarily always true. For example, we know that the accuracy of an EDM, GPS and/or VLBI baseline is proportional to the length of the baseline itself, which clearly indicates that the random errors of this type are proportional to the measured quantities. From the statistical point of view, such random errors should be multiplied to the functional models and are not additive any more. In this talk, we will extend the conventional model of geodetic adjustment to account for multiplicative errors and/or mixed additive-multiplicative errors. We will address the parameter estimation and error analysis in the linear/linearized model of measurements with mixed additive-multiplicative random errors. More specifically, we will first discuss three least-squares-based methods to estimate the model parameters, namely, least squares, weighted least squares (LS) and bias-corrected weighted least squares. We will then analyze these three methods from the statistical point of view. We construct five estimators of the variance of unit weight in association with the three LS-based methods and compare them, statistically and through numerical simulations. Although LiDAR data have been proved to be of multiplicative nature, they have been treated as if they were of additive random errors. Thus, as a final part, we will simulate a landslide example, which is supposed to be surveyed with LiDAR, to demonstrate how the methods discussed here works and how they can be applied to DEM construction for disaster monitoring.

*G06-P-07
IAG Symposium / IAG04. Positioning and Applications / G06. Geodetic remote sens
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Ionospheric parameters determination using integrated space geodetic data (case study: Iran)

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Ionosphere is a layer of the upper atmosphere, between the thermosphere and the exosphere, distinguished because it is ionized by solar radiation. As an important part of human living environment, ionosphere affects our modern society in many ways, e.g. International broadcasters use this medium to reflect radio signals back toward the Earth. In last decade space geodetic techniques have turned into a capable tool for studying the ionosphere. Up to now, two dimensional models of vertical TEC have been widely developed and used by different communities; however, due to the fact that these models provide information about the integral of the whole electron content along the vertical or slant ray path, these maps are not useful when information about the ionosphere at different altitude is required.
This paper includes the extraction of ionospheric parameters from radio signals observed by various space observation techniques; i.e. Ionospheric Radio Occultations measurements from Low Earth Orbit satellites and observations from Global Navigation Satellite Systems (GNSS). Due to the commonly heterogeneous distribution of the data, the selection of suitable basis functions is an important issue. For this reason we applied B-Spline basis functions. B-Spline basis functions are used for longitude and latitude variations of the electron density and Chapman profile function for altitude variations. The required data for our investigation are ground based measurements of permanent GPS stations over Iran and radio occultation data from Formosat-3/Cosmic for region of interest.
The National Cartographic Center of Iran (NCC) has established a network of one hundred GPS stations: The Iranian Permanent GPS Network for Geodynamics. By integrating observations from various observation techniques, it is expected to have an increase in accuracy and reliability of final model of electron density.

Ionospheric scintillation detection based on GPS observations, a case study over Iran

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The earth's upper atmosphere –the ionosphere– is a highly variable region with complex physical structure which is produced by ionizing radiations from the sun. a layer of ionosphere, extended from 250 to 400 km above the earth's surface which contains the greatest amount of free electrons, is called F-region. During strong geomagnetic activities, this region would be disturbed; also small-scale irregularities in electron density would be developed. Signals from Global Positioning System (GPS), pass through this region before reaching receivers on the Earth and therefore if the irregularities are sufficiently enough, signals may experience rapid amplitude fluctuations or unexpected phase changes. This is referred to as ionospheric scintillation. Ionospheric scintillation is one of the dominant propagation disturbances at radio frequency signals. These irregularities severely affect the accuracy and reliability of GPS measurements. Therefore it is necessary to investigate ionospheric scintillation and its effects on GPS observations.
The focus of this paper is to detect ionospheric scintillations over Iran's region, during different periods of solar activity and to investigate these effects on GPS observations in more detail. Furthermore the effects of these irregularities on regional modeling of ionosphere over Iran is also investigated. The results show that effectiveness of this phenomenon depends on geographic location, local time and global geomagnetic storm index (kp index).
The required data for this investigation are ground based measurements of permanent GPS stations over Iran, established by the National Cartographic Center of Iran (NCC).

*G07-1-01
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (GGOS) and Earth monitoring services

The Contribution of Geodetic Observations to Science and Society

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Earth observations are needed not only for scientific research but also for societal applications such as disaster prevention and mitigation, managing resources like energy, water, and food, mitigating the effects of climate change, and protecting the biosphere, the environment, and human health. Geodetic observations provide the metrological foundation for Earth observations and provide the means to determine mass transport in the Earth system. Geodetic observations are therefore a cornerstone of the Earth observing systems needed for scientific research and societal applications. Geodetic observations also provide the basis for realizing the reference systems that are required in order to assign coordinates to points and objects in space and time and to describe the motion of the Earth in space. The International Terrestrial Reference Frame (ITRF) determined by geodetic observations is the indispensable foundation for all the sustainable Earth observations that are used by science and society for so many purposes, including navigation, mapping, surveying, construction, land development, natural resource management and conservation—in fact, all decision-making activities that have a geo-related component. It allows different spatial information, such as imagery from different space and airborne platforms, to be geo-referenced and aligned with each other. And it plays a key role in modeling and estimating the motion of the Earth in space, in measuring change and deformation of all components of the Earth system, and in providing the ability to connect measurements made at the same place at different times, a critical requirement for understanding global, regional and local change. In this presentation, selected examples of the contribution of geodetic observations to science and society will be presented.

*G07-1-02
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (GGOS) and Earth monitoring services

The GGOS Bureau of Networks and Observations: Activities and Plans

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Working with the IAG geometric services (VLBI, SLR, GNSS, and DORIS) the Bureau continues to advocate for the expansion and upgrade of the space geodesy networks for the maintenance and improvement of the reference frame and other application, and for the extension and integration with other techniques. New sites are being established following the GGOS concept of “core" and co-location sites; new technologies are being implemented to enhance performance in data yield as well as accuracy. Several groups are undertaking initiatives and seeking partnerships to update existing sites and expand the networks in geographic areas currently void of coverage. The Bureau continues to meet with organizations to discuss possibilities of new and expanded participation and to promote the concept of partnerships. The Bureau provides the opportunity for representatives from the services to meet and share progress and plans, and to discuss issues of common interest. The Bureau monitors the status and projects the evolution of the network based on information from the current and expected future participants. Of particular interest at the moment is the integration of gravity and tide gauge networks. The Committees and Joint Working Groups play an essential role in the Bureau activities: using simulation and analysis techniques to project future network capability and to examine trade-off options, working on strategies for GGOS metadata systems, enhancing communication with the space missions and advocating for missions that support GGOS goals, working to enhance standardization in ground survey procedures and encouraging participation of new survey groups.

The 2007–2018 Implementation Plan for the GGOS Bureau of Networks and Observations has been posted on the GGOS website. We will outline progress over the past two years and discuss the status of the network and updated plan.

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GGOS Bureau of Products and Standards: Recent activities and future plans

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The Bureau of Products and Standards (BPS) supports GGOS in its goal to obtain consistent products describing the geometry, rotation and gravity field of the Earth, along with its variations in time. The main purpose of the BPS is to keep track of adopted geodetic standards and conventions across all IAG components as a fundamental basis for the generation of consistent geometric and gravimetric products. The work of the BPS is primarily built on the IAG Service activities in the field of data analysis and combinations. The BPS acts as contact and coordinating point regarding homogenization of standards and IAG products. As a key activity the BPS has performed an assessment of the standards and conventions currently adopted and used by the IAG and its components for the processing of geometric and gravimetric observations and as a basis for the generation of IAG products. The results of this BPS inventory were published in the IAG Geodesist's Handbook 2016.

In this contribution we present the role of the BPS and summarize the major findings of its recent activities. Some examples of the product-based BPS inventory on standards and conventions will be highlighted. It will also be discussed how to proceed with the recommendations given in the inventory and how to resolve inconsistencies and gaps in order to improve the consistency of IAG products. This presentation will also give an overview of the contributions of the BPS towards the integration of geometric and gravimetric parameters and the development of new products, required to address important geophysical questions and societal needs.

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Space Geodetic Activities and GGOS Working Group in Japan

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Japan has been actively involved in space geodetic observations, technical developments and data analyses since 1970s. Eminent long-term examples are Shimosato Hydrographic Observatory for SLR (Satellite Laser Ranging), GSI (Geospatial Information Authority of Japan) Tsukuba Station and NIPR (National Institute of Polar Research) Syowa Station for VLBI (Very Long Baseline Interferometry), and NICT (National Institute of Information and Communications Technology) being one of the VLBI Technical Development Centers. More institutes and individuals have a number of achievements.

Japanese geodetic activities had leaned a little to monitoring local and regional deformation. At the early stage of IAG GGOS (Global Geodetic Observing System), Japan did not present much involvement, but the “GGOS Working Group" was formed in 2013. Helped by a number of institutes and organizations, the Geodetic Site List was assembled in 2014 where 10 geodetic sites in Japan and one geodetic site in Antarctica were included. Each site has at least one VLBI or SLR station collocated with a GNSS station, and some of them has a DORIS antenna and a gravimeter. The list was submitted to the GGOS bureau and all sites were approved as a GGOS site. It should be noted that 5 different institutes own and operate these sites. Each of them has its own backgrounds and missions but all of them have worked in collaboration.

Due to seismic deformation, especially the 2011 Tohoku Earthquake, the motion of the geodetic sites in Japan cannot be properly expressed by the conventional piecewise linear function. However, the use of post-seismic deformation models newly introduced in ITRF2014 is expected to ease the problem, and the Japanese stations can contribute to global-scale geodetic products.

The GGOS WG of Japan strives to improve the quality and productivity of our geodetic stations, to encourage the collaboration beyond each technique, and to make/help strategic projects for the future.

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Observing the Earth's gravity field as integral component of the Global Geodetic Observing System

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Observing the Earth's gravity field addresses in several aspects the mission of GGOS. It provides a) the direct observation of mass variations (due to geophysical signals) and mass transport processes, b) a physical height reference surface, with respect to which very small change processes can be described, and c) the definition of the datum of the terrestrial reference frame.
The first generation of satellite gravity missions (CHAMP, GRACE, GOCE) has revolutionized our picture of the static and time-variable gravity field. However, due to signal attenuation with altitude gravity models based on satellite data are restricted to 70-80 km wavelength, so that a combination with ground data is still indispensable for high-resolution applications such as the definition and global unification of height systems. Service applications with significant societal benefit such as forecasting of floods and droughts or water management require not only a higher spatial resolution, but also the provision of the temporal changes of the gravity field in near real-time.
In this paper the achievements, but also limitations of the current observation of the Earth's gravity field are discussed. An inventory of the GGOS satellite infrastructure, which is needed to achieve the GGOS 2020 goals, performed by the GGOS Standing Committee on Satellite Missions, has revealed that that gravity field missions are the most critical component to be continuously maintained in the future. Therefore, current international activities to advocate satellite gravity missions and thus to foster a sustained gravity field observations system from space as integral component of the GGOS satellite infrastructure in the future are presented, and the added value of improved measurement technology and innovative mission concepts is discussed. Finally, special emphasis will be given to the gravity field contributions to a globally unified height system as integral part of a Global Geodetic Reference Frame.

*G07-1-06
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A first approximation to the International Height Reference Frame (IHRF)

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The International Height Reference System (IHRS) is defined as a geopotential reference system co-rotating with the Earth. Coordinates of points attached to the solid surface of the Earth are given by (1) geopotential numbers C(P) referring to the equipotential surface defined by the conventional W0 value 62636853.4 m2s-2 and, (2) geocentric Cartesian coordinates X referring to the International Terrestrial Reference System (ITRS). The determination of the coordinates C(P) and X(P) includes their variation with time. As W0 is a conventional constant value, C(P) basically depends on the potential value W(P). Thus, W(P) may be understood as a main coordinate of the IHRS. The present challenge is the realization of the IHRS; i.e., the establishment of the International Height Reference Frame (IHRF). This comprises, among others, (1) the selection of a global well-distributed set of stations as the IHRF core network, and (2) the development of strategies for the precise computation of the coordinates W(P) and X(P) at those core stations. While X(P) may be determined following the standards and conventions of the International Earth Rotation and Reference Systems Service, the estimation of the potential values W(P) is not a standardized procedure so far. Consequently, the establishment of the IHRF also includes the identification of harmonized standards for the consistent determination of W(P) and X(P), the precise modelling of the time-dependent changes of the coordinates, and the implementation of strategies for the collocation of IHRF reference stations with other reference frames (like the GGRF, the ITRF, geodetic observatories, time laboratories, etc.). This contribution presents the first approximation to the IHRF: it describes the preliminary IHRF core network and the criteria applied to select its reference stations. It also discusses and compares different approaches for the computation of the potential values W(P) at the IHRF core stations.

*G07-2-01
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Activities of the UN GGIM on the Global Geodetic Reference Frame

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The United Nations initiative on Global Geospatial Information Management (UN-GGIM) plays a leading role in setting the agenda for the development of global geospatial information and promoting its use in addressing key global challenges. It provides a forum for liaison and coordination between Member States, and also between Member States and international organizations. Recognizing the importance of the Global Geodetic Reference Frame (GGRF) for science and societal applications the UN GGIM facilitated a group of interested member nations and international organisations, including the IAG, to commence cooperation on global geodesy under the auspices of the UN. This presentation will detail the achievements so far including the adoption of a UN General Assembly Resolution on Geodesy and the development of a Roadmap for the sustainability and enhancement of GGRF. It will also discuss plans for the development of an implementation plan for the GGRF Roadmap.

*G07-2-02
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (GGOS) and Earth monitoring services

Roadmap to implement the UN resolution on Global Geodetic Reference Frame in Europe

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In February 2015 the United Nations General Assembly adopted the resolution on a Global Geodetic Reference Frame for Sustainable Development (A/RES/69/266), recognizing the importance of a globally coordinated approach to geodesy. The plan and the roadmap were formulated by the working group on the Global Geodetic Reference Frame (GGRF) of the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM).

UN-GGIM has regional entities, including UN-GGIM:Europe. In connection with the implementation of the GGRF roadmap it is assumed beneficial that the regions contribute through regional GGRF working groups. The UN-GGIM: Europe working group “GRF-Europe" (Geodetic Reference Frames – Europe) was established in 2016 to prepare and implement the plan in Europe. GRF-Europe will be working with a close connection to geodesy-related organizations in Europe and actively contribute to the work of the sub-committee on Geodesy in UN. GRF-Europe will provide a link between the geospatial community, scientists and policy makers. In this presentation we will describe current status and plans of GRF-Europe.

*G07-2-03
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Recent Activities of the GGOS Standing Committee on Performance Simulations and Architectural Trade-Offs (PLATO)

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The terrestrial reference frame (TRF) is the foundation for virtually all space-based and ground-based Earth observations. The commonly used global TRF is the International Terrestrial Reference Frame (ITRF) that is generated by combining the observations of GNSS, VLBI, SLR and DORIS. GGOS has determined that the accuracy and stability of the ITRF, suitable for a global society on a changing planet, needs to be better than 1mm and 0.1mm/y, respectively. As these goals are not yet reached, several improvements are needed:
Developing next generation space-geodetic stations with improved technology and system performance;
Improving the ground network configuration in view of global coverage and co-locations;
Improving the number and accuracy of surveys between co-located stations;
Deploying, improving and optimizing space-based co-locations.

In order to support these activities, GGOS established the Standing Committee "Performance Simulations and Architectural Trade-Offs (PLATO) “. To achieve progress in the topic mentioned above the PLATO members develop improved analysis methods using all existing observation data and co-locations of space-geodetic techniques. In addition, extensive simulations are carried out in order to investigate future improvements and optimization of the ground network, the space segment and different observation scenarios. These simulations will help to assess future data product quality based on projected network configuration and performance. Since 2015, PLATO acts also as Joint Working Group under IAG's Sub-Commission 1.1.

This presentation summarizes the activities within the Standing Committee PLATO and gives an overview on our ongoing studies. Preliminary results will be highlighted and first recommendations will be given.

*G07-2-04
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Simulated multi-technique TRFs for GGOS with focus on enhanced SLR and VLBI ground network architecture

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One of the key tasks of the Global Geodetic Observing System (GGOS) is the provision of high quality and consistent global terrestrial reference frames (TRFs) to accurately monitor and reliably interpret important geophysical processes such as the global sea level rise. The GGOS requirements of 1 mm accuracy and 0.1 mm/yr stability in the long-term are not achieved so far by the currently available TRFs due to, e.g., the lacking of an optimal architecture of the ground networks of the Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) space-geodetic techniques. In this study we address this issue by assessing the merit of enhanced SLR and VLBI networks. We simulate all four space geodetic techniques (Doppler Orbitography and Radiopositioning Integrated by Satellite - DORIS and Global Navigation Satellite Systems - GNSS besides SLR and VLBI) contributing to the TRF in the time span 2008-2014 and combine them by applying simulated local ties (LTs). From the combination of SLR and VLBI we conclude that the precision of the LTs should be 1 mm or better. Simulating LTs with systematic errors indicates that the stations Wettzell, Badary and AGGO play a key role in the combination and should definitely be precise to 1 mm or better. Simulating enhanced VLBI networks, which are expected to be operational in 5 and 10 years from now, demonstrate that the anticipated network in 10 years fulfills the 1 mm GGOS goal in terms of the TRF defining parameters. In the end, our simulation tool allows to assess the impact of the LT accuracies and their monitoring intervals and to identify beneficial new co-location sites to improve the TRF in order to achieve the GGOS goals.

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Effective expansion of satellite laser ranging network for improving geodetic products and satellite orbits

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About 35 satellite laser ranging stations are being operational all over the world but huge regions on the globe are not covered. We assume a new station is going to be added to the existing station network and therefore we like to evaluate the effectiveness of each location. Realistic numbers of observations for a new station are numerically simulated, based on the actual data acquisition statistics of the existing stations. Multiple-satellite-combined orbit determination is then conducted with and without a new station, and the estimated errors are investigated.

A new station placed in the Southern hemisphere is found to be effective in general. It is revealed that the most effective place differs according to the geodetic parameter. The X and Y components of the geocenter and the sectoral terms of the Earth's gravity field are largely improved by a station in the polar regions. A middle latitude station best contributes to the tesseral gravity terms, and, to a lesser extent, a low latitude station best performs for the Z component of the geocenter and the zonal gravity terms. With the existing stations the quality of satellite orbits is found to be relatively poor in the Southern hemisphere, but a new high latitude station in Antarctica enhances locally the accuracies so they behave close to uniform over one orbit.

*G07-2-06
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Benefits for GGOS from SLR tracking of GLONASS, Galileo, BeiDou, and QZSS satellites

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One of the fundamental goal of GGOS is to improve the consistency level between different space geodetic techniques, such as Global Navigation Satellite Systems (GNSS) and Satellite Laser Ranging (SLR). In the SLR solutions, the station coordinates are typically derived on the basis of SLR tracking of four spherical geodetic satellites: two LAGEOS and two Etalons. The GNSS orbits are, on the other hand, solely derived from microwave GNSS observations. The International Laser Ranging Service (ILRS) initiated four intensive SLR tracking campaigns for Galileo and three campaigns devoted to tracking all GNSS spacecraft between 2014 and 2016. As a result, the number of SLR observations and the number of tracked GNSS satellites have dramatically increased allowing for determining GNSS orbits, SLR station coordinates, and Earth Rotation Parameters (ERPs) solely on the basis of SLR tracking of GNSS satellites.

We will present a solution in which the GNSS orbits, SLR station coordinates, geocenter coordinates, and ERPs are determined using the SLR observations to 26 GLONASS, 14 Galileo, 2 BeiDou IGSO, 2 BeiDou MEO, and 1 QZSS satellite. We compare the SLR station coordinate stability derived from GNSS-based results to the LAGEOS-only solution and from a combined 'SLR to GNSS+LAGEOS' solution. We compare as well the SLR-derived GNSS orbits to the microwave-derived results. We found that the coordinate stability of those SLR stations which provide a large number of SLR observations of GNSS s/c can remarkably be improved. The Length-of-day parameter can be derived from SLR-GNSS solutions with a much better accuracy than from the LAGEOS-only solutions. The benefits for ITRF of SLR tracking of GNSS satellites are much greater than the SLR tracking of two Etalons. Eventually, we show that the SLR tracking of GNSS satellites improves the consistency between SLR and GNSS solutions, which is fundamental for fulfilling the GGOS goals.

*G07-3-01
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Implementing the GGOS Decadal Vision for Geohazards Monitoring

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The Global Geodetic Observing System of the IAG identified present and future roles for Geodesy in the development and well being of the global society. The GGOS is focused upon the development of infrastructure, information, analysis, and educational systems to advance the International Global Reference Frame, the International Celestial Reference System, the International Height Reference System, atmospheric dynamics, sea level change and geohazards monitoring. The geohazards initiative is guided by an eleven nation working group initially focused upon the development and integration of regional multi-GNSS networks and analysis systems for earthquake and tsunami early warning. The opportunities and challenges being addressed by the Geohazards working group include regional network design, algorithm development and implementation, communications, funding, and international agreements on data access. This presentation will discuss in further detail these opportunities and challenges for the GGOS focus upon earthquake and tsunami early warning.

*G07-3-02
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Global Navigation Satellite System Tsunami Early Warning Project

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The past decade has witnessed a terrible loss of life from large earthquakes and resultant tsunamis in the Indo-Pacific region. Algorithms based on real-time GNSS data and science now exist to rapidly determine the likelihood that a tsunami will be generated from a large earthquake, to predict their extent, inundation, and runup, and to track the tsunami as it propagates through the ocean basins. The algorithms use real-time GNSS in combination with other sensors to measure ground displacements generated by large earthquakes to quickly estimate critical parameters (magnitude, depth, length, spatially slip distribution along strike and dip of the fault, rupture direction) used to assess the likelihood that earthquake generated a tsunami and then to measure disturbances in the ionosphere generated by the propagating tsunamis. An experimental prototype GNSS-based tsunami early warning system could be developed that would initially incorporate real-time data from existing networks in economies around the circum- and intra- Pacific and Indian Ocean basins. This prototype requires access to real-time GNSS data distributed throughout earthquake and tsunami prone regions. In this talk, we discuss this technology and its considerable promise. We also report on a workshop, funded by NASA, to understand the feasibility of deploying such a system around the Pacific Rim during the next decade. The workshop, to be held in Sendai during July 25-27, 2017, has the goals:

- Identify what GNSS resources (networks, processing centers, telecommunication, etc.) will be necessary to develop real-time GNSS early warning capabilities throughout the entire Pacific Rim region
- Assess data gaps in the current Pacific-wide networks, develop strategies on the best approaches to fill the gaps
- Review the state-of-the-art early warning approaches with an eye towards emergency response community.

We conclude with a summary of actionable items to be carried out following this workshop.

*G07-3-03
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GNSS Buoy Array in the Ocean for a Synthetic Geohazards Monitoring System

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The GNSS buoy system for tsunami early warning has been developed and is now operational as a national wave monitoring system since 2008 in Japan. It was used to update the tsunami warning at the 2011 Tohoku-oki tsunami, Japan. Yet, the buoys are placed less than 20km from the coast and are not far enough for effective evacuation. We are thus trying to improve the system for putting the buoys much farther from the coast. For this purpose, we employ a new PPP-AR analysis algorithm, instead of conventional RTK-GPS, for positioning. In addition, a two-way satellite data transmission in contrast with current surface radio system is introduced. We have conducted a series of experiments using the upgraded system in 2013 and 2014, using a buoy located about 40km south of Cape Muroto, southwest Japan. GEONET data were used to obtain precise orbits and clocks of satellites, and the information was sent to the buoy using a satellite. The information was used for real-time PPP-AR analysis for every second. The estimated buoy position was then sent back to the ground base through another satellite. The received data was disseminated to public through internet. These experiments indicate that the GNSS buoy can be placed at nearly anywhere in the ocean. Given this success, we made up a new research plan in which we test a commercially available satellite communication system and try to develop a new GNSS-acoustic system for continuous monitoring of ocean bottom crustal movements. Moreover, we are trying further applications of GNSS data for ionospheric and atmospheric researches. A new project started in June 2016 which tries to establish a GNSS buoy array in the western Pacific, which will be a powerful tool for monitoring geohazards in the region. The newly designed GNSS system is deployed at another buoy located about 40km south of Cape Ashizuri, southwest Japan. The system is now under testing. We are adding a GNSS-acoustic system in 2017 to the same buoy.

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Global and regional sea level budgets from joint analysis of space gravimetry and altimetry data sets

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Partitioning of altimetric sea level change in contributions from ocean steric expansion, ice-sheet and glacier mass imbalance, the water cycle, and crustal uplift is important for developing sea level predictions at the regional scale, but as yet our understanding is incomplete even on the global scale.

Here we will present updated results following the ‘inverse' method developed at the University of Bonn, where budget closure is imposed on altimetric and gravimetric data in a least-squares forward modelling - inversion scheme (Rietbroek et al., 2016). Starting with GRACE normal equations and along-track binned Jason-1 and -2 altimetry, we derive an ocean mass rate at the lower end of the spectrum of contemporary studies (-0.3 mm/a hydrology, 1.4 mm/a ice sheets and glaciers, 2002-2014) that would suggest a larger steric rate than found from conventional ‘direct' GRACE ocean mass estimates before, but consistent with several modelling studies. As an aside, geocenter motion (difference between the center of common mass, CM, and the center of surface figure, CF) is resolved for within the method itself and can be extracted as a byproduct; i.e. we do not rely on external data for it.
In particular, we will discuss the sensitivity of these inversion results with respect to GRACE and altimetry data sets: we will present new results that incorporate Envisat altimetry and Swarm satellite gravimetry (which may be relevant in case a gap between GRACE and GRACE-FO cannot be avoided).

Rietbroek R. et al. (2016): Revisiting the contemporary sea-level budget on global and regional scales, Proc. Nat. Acad. Sci. U.S.A. 113(6):1504–1509

*G07-3-06
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The International DORIS Service: Current Status and Future Plans

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The International DORIS Service (IDS) was created in 2003 under the umbrella of the International Association of Geodesy (IAG) to foster scientific research related to the French DORIS tracking system and to deliver scientific products, mostly related to the International Earth rotation and Reference systems Service (IERS). Since its start, the organization has continuously evolved, leading to additional and improved operational products from an expanded set of DORIS Analysis Centers.
IDS is now based on a reinforced structure with two Data Centers, six Analysis Centers, several associated groups and a Combination Center. Using the experience gained in the preparation of the ITRF2008 and ITRF2014, many improvements were made both in data analysis and on technical aspects.
This presentation addresses the organizational aspects of the IDS and the recent achievements made by its components. We also discuss the future plans in terms of new products and activities.

*G07-4-01
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Activities of the Wettzell station in Germany

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The geodetic observatory in Wettzell (Germany) has a long tradition in geodetic observations for VLBI, SLR, GNSS and gravimetry, and the observatory has recently been augmented with a DORIS beacon. By this additional instrumentation, Wettzell is one of only four global geodetic observatories that are equipped with all four space geodetic techniques. Such kind of geodetic stations are of great importance for generating a stable global geodetic reference frame because co-locations of the four geodetic space techniques are crucial for consistently combining the contributions by all observing techniques.
With three VLBI telescopes – the "old" RTW with one of the longest observing history, and the new TWIN telescopes – Wettzell is a key player in the international VLBI community. The participation in diverse 24-hour sessions guarantees a stable and continuous contribution to the global reference frame. Additionally, the almost continuous participation in the Intensive sessions is the basis for a reliable and continuous determination of Universal Time with low latency, which is required for every navigation application and every satellite mission.
An important aspect at co-located sites is the determination and monitoring of the co-location network. Besides local survey campaigns in regular intervals, Wettzell is installing an inter-technique calibration target which does not only function as geometric reference for all techniques but also allows to monitor the potential differences in the timing system between the individual instruments.

*G07-4-02
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (GGOS) and Earth monitoring services

Geodetic activities at Syowa Station, East Antarctica

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Syowa Station, the main wintering base of the JARE (Japanese Antarctic Research Expedition), is located on East Ongul Island, Dronning Maud Land, East Antarctica. Three space geodetic observations with VLBI (Very Long Baseline Interferometry), GNSS (Global Navigation Satellite System) and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) have been carried out at Syowa Station since the 1990s and these observation sites are all distributed within 400m each other. We have also conducted repetitive absolute gravity measurements with FG-5 and temporal gravity change measurements with three serial superconducting gravimeters since early 1990s. For monitoring ocean tides and sea level, tidal observation with bottom pressure gauges has been continuing at Nisi-no-ura Cove, 700 m far from GNSS sites, since 1976. Their local ties have been surveyed with accuracy less than a few millimeter, except that vertical offset vector between GNSS and VLBI was determined with an uncertainty of 1 cm.

Those continuous geodetic observation data contributed to maintain international terrestrial reference frame and to detect crustal movement induced by glacial isostatic adjustment and recent surface mass changes on East Antarctic ice sheet. To enhance the geodetic observations, we start a feasibility study for installing SLR (Satellite Laser Ranging) system at Syowa Station.

In this study, we report the current geodetic activities of JARE at Syowa Station, and the future plans for contributing to GGOS as a co-location site in Antarctic region.

*G07-4-03
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (G GOS) and Earth monitoring services

Development of New Analysis Strategy for GNSS Observation Network in Japan

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Geospatial Information Authority of Japan (GSI) has been operating Continuous Operating Reference Stations (CORS) called GEONET (GNSS Earth Observation Network System), since 1996. We currently operate more than 1,300 stations to cover whole Japan, with an average spacing of about 20km. With the total number and density, GEONET is one of the largest GNSS CORS systems in the world. After 20 years of successful operation, it becomes vital infrastructure for surveying and mapping, precise positioning, disaster management, and even for weather forecast in Japan.
We calculate the daily coordinates for each GEONET station by using Bernese GNSS software to monitor the crustal deformation in Japan. The analysis strategy was updated three times. Latest version was established in 2009. We are now developing new strategy because the software, reference frame, and other physical models have been obsolete.
In this paper, we focus on the GPS and GLONASS integration. Only GPS was used for older strategy. However, the receivers and antennas in GEONET were updated into the multi-frequency type in 2013. Furthermore, the final orbit for GLONASS provided by IGS has reached almost the same accuracy in comparison with the one for GPS. We process GPS and GLONASS data independently to estimate the ambiguities, and then combine the solutions with normal equations. The result based on GLONASS observations data show the apparent fluctuation with the period of 8 days that was not found on the GPS result. Which is significant for the stations apart from the reference station, but it is systematic which can explain, for example, frame rotation. IGS analysis centers using GLONASS observations reported the same phenomenon that seemed to be caused by the GLONASS constellation geometry (Ray et al., 2013, Rebischung et al., 2016). We have tried ways to set transformation parameters and absorb systematic fluctuation. We discuss the method to suppress the apparent fluctuation in our presentation.

*G07-4-04
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Performance of various homogenization tools on a synthetic benchmark dataset of GPS and ERA-interim IWV differences

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Within the COST Action ES1206 “Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate" (GNSS4SWEC), a sub-Working Group (WG) on “Data Homogenization" has been set up. The aim of this group is to homogenize a worldwide Integrated Water Vapour (IWV) dataset retrieved from Global Positioning System (GPS) observations, the IGS repro 1 tropospheric product (1995-2010), by correcting for (artificial) break points due to e.g. instrumental changes. As at most stations, the ERA-interim IWV field output correlates well with the IWV retrieved by GPS, the former one is used as reference and the IWV differences between both sets are considered. The characterization of these IWV differences provided us typical trend values, seasonal oscillations and noise models, to build a synthetic benchmark IWV dataset of differences. We simulated these IWV differences over a period of 16.4 years with two different noise types: white, as well as the combination of white and autoregressive process. Then, we simulated offsets, trends and seasonal oscillations, as characterized from the real IWV differences. We created three variants of synthetic datasets referred to as: EASY, LESS-COMPLICATED and FULLY-COMPLICATED, depending on the level of complexity. All synthetic datasets were then subjected to homogenization: various detection methods (e.g. HOMOP, CLIMATOL, PMTred, STARS and non-parametric rank tests) were blindly employed to deliver the epochs of simulated offsets. In this presentation, we show the detection scores for each synthetic dataset type and each detection method We analyze the sensitivity of each detection method w.r.t. the complexity of the synthetic datasets. We also present the trend differences between before and after homogenization by the different approaches.

*G07-4-05
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A comparison of precipitable water vapor retrieved with novel ground-based microwave radiometer, GPS and analysis data in Tsukuba during a cold front passage

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We have developed a state-of-the-art microwave radiometer named KUMODeS (KEK Universal Moisture and Oxygen Detection System) using the technology of millimeter-wave spectroscopy for the high-resolution and high-precision monitoring of water vapor behavior. We have carried out comparative measurements of precipitable water vapor (PWV) in order to investigate the potential of KUMODeS/PWV measurements.

KUMODeS measures spectra using two receivers with frequency bands of 20–30 GHz and 50–60 GHz. The low-noise amplifier of the first receiver and a cold calibration source are implemented in a cryostat, which is maintained at 10 K in order to improve the sensitivity in the detection of the characteristic broad peak of water vapor at around 22 GHz. The second receiver is used to measure the absorption peaks of oxygen (~60 GHz).

The GPS-based PWV is estimated reliably with 1–2 mm accuracy according to previous studies. The GPS PWV values are retrieved from zenith wet delays (ZWDs), which are computed by subtracting the zenith hydrostatic delays (ZHDs) from GPS-based zenith total delays (ZTDs). In this procedure, the ZHDs are obtained from the surface pressure and temperature.

We analyzed the PWV variation in Tsukuba, Japan, derived from three techniques, i.e., using KUMODeS, GPS and JMA operational local analysis (LA), during a cold front passage. The PWV measurements derived from GPS and KUMODeS have temporal resolutions of 30 s and about 2 min, respectively. The estimates from the LA have a temporal resolution of 1 h. A comparison of time series shows good agreement between the PWV measurements retrieved from KUMODeS, GPS and the LA between 20 and 22 December 2016. On the other hand, some differences between them appeared after the heavy rainfall of 22 December.

Although further investigation is required to evaluate the performance of KUMODeS, the preliminary result of the comparison implies the consistency and potential of KUMODeS measurements.

*G07-4-06
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Solar radiation pressure acceleration acting on geodetic satellites: precise orbit determination vs surface materials

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Satellite orbits are subjected to various non-gravitational forces and solar radiation pressure has been one of the major error sources in orbit determination. Solar radiation pressure acting on a satellite depends on how sunlight illuminates its surface and is reflected there. The cannonball model is widely applied for spherical geodetic satellites. In this model, the scale factor of the actual acceleration in comparison with an ideal spherical black body case is expressed by a solar radiation pressure coefficient C_R.
This study attempts to relate the behavior of the C_R solutions derived from precise orbit determination with the optical properties of the satellites' surface.
We use the geodetic analysis software “c5++" (Otsubo, 2016) to estimate the solar radiation pressure coefficients C_R of the six geodetic satellites: Ajisai LAGEOS-1, LAGEOS-2, LARES, Starlette and Stella. Satellite laser ranging data for the past 20 years are analyzed where the C_R coefficients are estimated per 30 days.
It is clearly seen that the estimated C_R values for Ajisai, 1.041 on average, are smaller than those of other satellites, ranging from 1.075 to 1.164. This is explained by the fact that the surface of Ajisai is largely covered by mirrors where the surfaces of the other satellites are covered by a metallic body and corner cube reflectors.
In addition, this study deals with time variation of solar radiation pressure. When the optical properties of the satellite's surface were completely spherical symmetry, the C_R value would be constant. Sengoku (1995) predicted that the annual variation should dominate for Ajisai. However, our C_R solutions of Ajisai from precise orbit determination show a semi-annual periodic variation much larger than the predicted annual variation. We attribute the reason to a 5-cm-height metallic ring attached to one of the pole and the detailed material distributions both of which were not considered in the previous study.

*G07-5-01
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The VLBI Global Observing System and its link to GGOS

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The International VLBI Service for Geodesy and Astrometry (IVS) and its infrastructure constitutes one of the fundamental components of GGOS for two main reasons: VLBI is unique in its ability to determine UT1-UTC and the Earth's rotation axis in space (precession/nutation), and it is one of the two techniques to define the scale of the terrestrial reference frame. The latter quantity is tightly connected to the IVS observing network with its precise station coordinates and velocity components. Starting about five years ago, the IVS began implementing the new VGOS concept (VLBI Global Observing System) of fast slewing telescopes enabling a better sampling of the atmosphere and its refraction effects. Experience has been gathered from the on-going developmental sessions, and some preliminary results are available from these measurements. On the other side, the legacy network is still contributing results with very good long term stability. The observational data and the results of the IVS Analysis Centers are kept on openly accessible servers and, thus, form an indispensable contribution to the GGOS project.

*G07-5-02
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VGOS development for Ishioka 13-m antenna

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The Geospatial Information Authority of Japan (GSI) constructed a new VLBI facilities in Ishioka. It is designed for the next-generation VLBI system called VGOS, which is promoted by the International VLBI Service for Geodesy and Astrometry (IVS) in order to meet the requirements of Global Geodetic Observing System (GGOS). In addition to the VGOS facilities, Ishioka has GNSS Continuously Operating Reference Stations and a gravity measurement facility in order to contribute to GGOS as a core observatory.
Since February 2015, the Ishioka 13-m antenna observed legacy S/X sessions with Tsukuba 32-m to obtain accurate positions of the new site. Then, Ishioka has started the international observations dedicated for Earth rotation measurement taking over the role of Tsukuba 32-m from the beginning of 2017. In parallel with these legacy observations, we have carried out several broadband observations compatible with VGOS frequency setup. From August to September 2016, we installed a new signal chain including QRFH (Quadruple-ridged flared horn), up-down converters, and high speed digital samplers at Ishioka in order to participate in VGOS Trial sessions which were broadband observations coordinated by IVS. Several experimental broadband observations with Kashima 34-m of NICT and Hobart 12-m of AuScope were also performed, and the compatibility of equipment between Ishioka and other overseas stations was confirmed.
We report on the recent development of VGOS equipment and results of the legacy and broadband sessions for Ishioka.

*G07-5-03
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Broadband VLBI System GALA-V

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We have developed a broadband VLBI system named GALA-V, which is compatible with the VGOS (VLBI Global Observing System) specification. The development contains broadband receiver system, data acquisition system, and up to data processing software for precision delay determination. This system demonstrated sub-pico second precision VLBI delay measurement by one second of observation between Japanese domestic broadband VLBI stations: Ishioka 13m and Kashima 34m. We conducted a series of broadband VLBI experiments between two small telescopes installed at NICT(Tokyo) and NMIJ(Tsukuba) for measurement of clock difference between UTC(NICT) and UTC(NMIJ). Analysis results of these experiments proved that broadband VLBI system enables pico-second precision observation even with small diameter radio telescopes. Weighted RMS of post-fit residual delay were around ten and a few pico-seconds on 1.6m-2.4m antenna pair. The experiment results suggest that delay precision was improved to a sufficient level by broadband system, and the error of geodetic/clock analysis is dominated by atmospheric delay uncertainty.

*G07-5-04
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Strategies to improve precision, accuracy, and latency of current and future VLBI Intensive sessions

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The International VLBI Service for Geodesy and Astrometry (IVS) observing programs currently include 1-hour long VLBI sessions normally observed on one (IVS-INT1, IVS-INT2) or three baselines (IVS-INT3). These sessions are known as the Intensive (INT) sessions and their purpose is to provide daily UT1-UTC estimates. However, the short observation duration, the limited number of participating telescopes, and the timeliness requirements make operation and analysis of the INTs a challenging task. We carried out different studies that try to help solving some of the drawbacks of these single-baseline VLBI sessions. In doing so, various analysis strategies and the impact of auxiliary and a priori data were evaluated by re-analysing more than one decade of Intensive sessions observed on the Kokee-Wettzell baseline in fully automated and consistent manner. We find that the largest variability in the obtained UT1-UTC accuracy is related to the availability of high-quality a priori Earth Orientation Parameters. Concerning operational INT processing, one currently faces the problem that the observed VLBI group delays contain ambiguities which need to be resolved. This is usually performed in a semi-automated mode. Therefore, we implemented a fully automated robust ambiguity estimation method based on the L1-norm, which increased the successfully resolved sessions by at least 5 %. Another question which we addressed is related to the upcoming VGOS networks and the way how those can deliver ultra-rapid UTC-UTC products. Based on current INT networks and through extensive simulations we investigated optimal locations for tag-along stations which enable flexible scheduling of three-station network sessions which can provide UT1-UTC with high accuracy. The results from our investigations are important for the transition from the current VLBI to operational VGOS and pave the way for future high quality UT1-UTC products.

*G07-5-05
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Error budget analysis in Geodetic VLBI

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Source structure effects have remained an error source in geodetic VLBI for many decades, both because their impacts on geodetic VLBI have been underestimated, and because it was difficult to image such amounts of radio sources regularly. In this report, the magnitudes of structure effects and their influence on measurement noise will be discussed using closure delays, closure phases, source images derived from the geodetic visibility data, and the delay residuals of individual observables after VLBI data analysis. The error budget of structure effects, measurement noise, and all other error sources due to incomplete modeling in geodetic VLBI will be studied. This will greatly help us to have a good insight for the forthcoming VGOS.

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Status of the ESA Earth Explorer missions

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With the recent successes of ESA's Earth Observation Programmes, through the realization of highly successful Earth Explorers, the launch of the first in the series of operational Sentinel satellites for Copernicus, the development of sophisticated meteorological satellites, and with the rapidly increasing power of technologies for data processing, analysis and dissemination, Europe has entered a new era for the development and exploitation of Earth-observing satellites. An important part of these ESA Programmes are its science-driven Earth Explorer missions which are distinguished by unique scientific objectives, focused on some of today's most important urgent scientific concerns in order to respond to a broad range of demands, from the challenges of understanding climate change to supporting a multitude of human activities on Earth and measuring their impact on the natural environment.

As of today, four out of the seven approved Earth Explorer missions have been launched: GOCE (2009), SMOS (2009), CryoSat (2010), and Swarm (2013). The last three are successfully operating while GOCE reentered the atmosphere in 2013 as a successful conclusion to its extended mission. These satellites each carry fundamentally new instrument technologies and the data that they are reporting are yielding fundamentally new insights into different aspects of the Earth system. Four other Explorer missions: ADM-Aeolus, EarthCARE, Biomass and FLEX are in varying stages of development and are planned to be launched in the coming years.

This presentation will place the Earth Explorers in the context of ESA's Earth Observation Programmes, and will provide an overview of their respective scientific objectives and observational capabilities, together with some of the highlights of the Explorer missions in operation or main characteristics of the missions being currently built. Further, it will outline the expected next steps in the programme in the near future.

*G07-P-02
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The ISO Geodetic Registry and Related Standards

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The International Standards Organization Technical Committee 211 (ISO/TC 211) on Geographic Information/Geomatics has taken responsibility for establishing the ISO Geodetic Registry, a registry of international geodetic reference systems and transformations. Such a registry is needed primarily by GIS software to define the various reference frames and transformations they use. The data contained in the registry are the parameters defining geodetic reference systems and adopted transformations between them and need to be validated by official sources. The ISO Geodetic Registry has been defined in accordance with the ISO International Standard (IS) 19127. This standard defines the data elements required, as well as the rules for its maintenance, in compliance with IS 19135 (procedures for registration of items) and IS 19111 (describing the elements necessary to fully define reference systems). As specified in IS 19135, the ISO Geodetic Registry consists of an online information system or database with a user interface and web services for access, a Registry Manager hosting the Registry and taking care of its daily operations, and a Control Body that approves the content of the Registry. The Norwegian Mapping Authority is serving as the initial Registry Manager and has funded and hosted the registry management software. The Control Body consists of geodetic experts nominated by the TC 211 member and liaison organizations with its chair and vice-chair nominated by the IAG. The ISO Geodetic Registry was made publically available earlier this year, populated with an initial set of global and regional reference frames and their associated transformations. Further population of the Registry continues and geodetic agencies are encouraged to submit their own reference frames and transformations. We describe the parameters required to be entered for such reference frames and transformations and provide the status of revisions of the supporting standards IS 19111 and IS 19127.

*G07-P-03
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New design and facilities for the International Database for Absolute Gravity Measurements (AGrav): A support for the Establishment of a new Global Absolute Gravity Reference System

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After about 10 years of successful joint operation by BGI and BKG, the International Database for Absolute Gravity Measurements "AGrav" was under a major revision. The outdated user interface was replaced by a responsive, high level web application framework based on Python and built on top of Pyramid. Functionality was added, like interactive time series plots or a report generator and the interactive map-based station overview was updated completely, comprising now clustering and the classification of stations. Furthermore, the database backend was migrated to PostgreSQL for better support of the application framework and long-term availability.
As comparisons of absolute gravimeters (AG) become essential to realize a precise and uniform gravity standard, the database was extended to document the results on international and regional level, including those performed at monitoring stations equipped with SGs. By this it will be possible to link different AGs and to trace their equivalence back to the key comparisons under the auspices of International Committee for Weights and Measures (CIPM) as the best metrological realization of the absolute gravity standard. In this way the new AGrav database accommodates the demands of the new Global Absolute Gravity Reference System as recommended by the IAG Resolution No. 2 adopted in Prague 2015.
The new database will be presented with focus on the new user interface and new functionality, calling all institutions involved in absolute gravimetry to participate and contribute with their information to built up a most complete picture of high precision absolute gravimetry and improve its visibility. A Digital Object Identifier (DOI) will be provided by BGI to contributors to give a better traceability and facilitate the referencing of their gravity
surveys.
BGI mirror site : http://bgi.obs-mip.fr/data-products/Gravity-Databases/Absolute-Gravity-data/
BKG mirror site: http://agrav.bkg.bund.de/

*G07-P-04
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IGFS geoportal development for gravity, geoid, GGM and DEM data

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The International Gravity Field Service (IGFS) Central Bureau (CB) has recently been established at DGS/AUTH and one of its main activities has been the promotion of IAG gravity-field related services along with the development of a new, user-friendly website. One critical issue that needs to be incorporated by IGFS is to answer user needs in terms of providing reliable feedback as to what kind and what type of gravity-field related data one can retrieve from IGFS. With that in mind, IGFS has developed a dedicated gravity-field related geoportal with the sole purpose of organizing a modern, user-friendly and coherent one-stop point where the interested user can visualize the current data availability within BGI, ICGEM, ISG, and IDEMS. The developed geoportal is incorporated as an IGFS application within the dedicated IGFS application server using open-source solutions (GeoServer, OpenLayers, PHP, PostgreSQL) and the GSSH coastline for the presentation of a basic cartographic background. The geoportal itself is not intended to provide the data themselves, but it rather serves as a one-stop point for showing data availability and directing to the respective IAG service for data retrieval. In this work the main steps taken for setting up the server are outlined along with some examples of the available data and information that the user can retrieve.

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IGFS metadata for gravity and geoid. Structure, build-up and application module

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Gravity field related products have been the focus of almost all geosciences in the sense that they provide realistic representation of the physical properties of system Earth. The rigorous documentation and archiving of gravity field related data, either irregularly distributed and on a grid, has become mandatory in order to ensure coherent and unambiguous utilization by users and archiving in related data management servers and services. Given the above, the International Gravity Field Service (IGFS) has taken steps in order to generate metadata for gravity field and geoid related data so that fragmentation of databases at national and international level as well as user needs can be addressed. To that respect, the general structure of the gravity and geoid metadata has been generated, describing all necessary fields that the metadata should have, while an online PHP-based web application has been developed and became available as an IGSF product to assist users to generate metadata for their gravity-related information. In this work we describe the main characteristics of the metadata structure and give details on the developed web application. Finally, the dedicated IGFS application server, igfsapps.topo.auth.gr, is described and details on the incorporation of the gravity and geoid metadata application as an online IGFS service are provided.

*G07-P-06
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (G GOS) and Earth monitoring services

The Data Base of the International Geodynamics and Earth Tide Service (IGETS)

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The International Geodynamics and Earth Tide Service (IGETS) was established in 2015 by IAG. IGETS continues the activities of the Global Geodynamics Project (GGP, 1997-2015) to support geodetic and geophysical research activities using superconducting gravimeter data in an international network. IGETS provides time series to monitor temporal variations of the Earth's gravity field and surface deformation by long term records from ground gravimeters, tiltmeters, strainmeters and other geodynamic sensors. IGETS also continues the activities of the International Center for Earth Tides (ICET) in collecting, archiving and distributing Earth tide records of various geodynamic sensors.
The IGETS data base is hosted by GFZ and is accessible via http://igets.gfz-potsdam.de to the geodetic and geodynamics community as well as to all other interested data producers and users. At present, records from superconducting gravimeters at 34 stations worldwide are available. Level 1 products are raw gravity and local air pressure records with 1 minute sample rate. As a new feature, records with 1 or 2 seconds samples are already provided for a few stations. Level 2 products consist of gravity and air pressure data corrected for instrumental perturbations and ready for tidal analysis, which are derived from Level 1 datasets and computed by the University of French Polynesia. Residual time series after geophysical corrections considered as Level 3 products are derived from Level 2 datasets and computed by EOST.
A major benefit of IGETS is the provision of digital object identifiers (DOI) for the data sets of every station. This ensures a long term availability and an increased visibility as part of an international network but also a proper citation. As IGETS is aiming to present all kind of long-term geodynamic time series, interested station operators are cordially invited to contribute with their data sets and, in return, benefit from being part of the IAG service.

*G07-P-07
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (GGOS) and Earth monitoring services

Effects of tidal perturbation on the geopotential for application of precise clock comparison to long-distance leveling: Case study of Japan as coastal areas

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Recent engineering advancement of precise comparison of optical clocks at a great distance, targeting to an accuracy equivalent to 1 cm in height difference, sheds new light on accurate geodetic leveling over long distances. Based on the theory of relativity, the rate difference between the clocks reflects the geopotential difference between the clock locations. Deriving the geopotential difference from the clock rate difference, however, requires removal of significant perturbation on the geopotential associated with time-variable tides, for example.
Supposing the application of chronometric leveling to coastal regions such as Japanese islands, we concern about the perturbation due not only to earth tides (ET) but to ocean tidal loading (OTL). Here, we evaluate the magnitudes of differential perturbation (DP) due to both ET and OTL separately over different distances ranging from a few tens to a thousand of kilometers. The results show that over a distance of 50 km the temporal changes in combined DP due to ET and OTL can reach the magnitude of 1 cm in terms of equivalent height difference (EHD). Over a distance of 600 km OTL can produce DP with a peak-to-peak amplitude of 1 cm EHD, and over a distance of 1000 km even root-mean-square amplitudes of OTL-induced DP reach about 2 cm EHD. Therefore, future geodetic application of precise clock comparison to constraining a nationwide height datum over long distances must unavoidably take into consideration the removal of perturbation due not only to ET but to OTL.

*G07-P-08
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (GGOS) and Earth monitoring services

Activities of the Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV)

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The Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) was established in 2014 as a subgroup of the International VLBI Service for Geodesy and Astrometry (IVS) in order to foster regional collaboration of VLBI. AOV coordinates six regional sessions in a year on regular basis by sharing resources of scheduler, stations, and correlators. AOV members are also enhancing their close collaboration by sharing information of recent activities in several face-to-face meetings. Successful broadband VLBI experiments with telescopes in Australia and Japan in August 2016 marked the start of VGOS in this region under the collaboration of AOV. We talk on the recent activities of the AOV.

*G07-P-09
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (GGOS) and Earth monitoring services

Geodetic Observations in Mizusawa VLBI Observatory

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Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, is operating many geodetic observation systems such VLBI, GNSS and gravimeters. For the VLBI observation, we commenced constructing VERA (VLBI Exploration of Radio Astrometry) in 2000. VERA consists of four VLBI stations and each station has a 20m antenna. We started regular geodetic VLBI observations with VERA in 2004. One of VERA stations joins in IVST2 and AOV networks at present. For the GNSS observations, we are operating GPS observations at VERA stations. Also, we are operating an IGS station and a GESS (Galileo Experimental Sensor Station) in the Mizusawa campus in cooperation with GFZ Potsdam. For the gravity observation, we had been operating gravity change observation with a superconducting gravimeter at Esashi Earth Tides Station for the year 1988-2008, and have been operating similar observation at Mizusawa since 2009 until now. In the Mizusawa campus, all of these facilities are located within 250m area and collocated observations are performed. We introduce those geodetic observations systems in Mizusawa VLBI Observatory. Besides we introduce several observation results including those at the Tohoku Earthquake in 2011 obtained with the different techniques.

*G07-P-10
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (GGOS) and Earth monitoring services

Development of Wideband Antennas

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Wideband antennas for VLBI were developed and reported in this poster.
Wideband feeds and OMTs were newly developed to upgrade Kashima 34m antenna and small portable VLBI stations named MARBLE of NICT.
Our project, named Gala-V, uses 3.2-14.4GHz with NINJA feeds and 6.5-15GHz with IGUANA-H feeds.
Wideband geodetic observation, methanol masers observations of 6.7 GHz and 12.2 GHz in same time and other various wideband radio astronomical observations are capable now with these antennas in Japan.

*G07-P-11
IAG Symposium / IAG05. IAG Joint / G07. Global Geodetic Observing System (GGOS) and Earth monitoring services

Contribution for international geodetic frame of SLR observation at the Shimosato Hydrographic Observatory

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The Hydrographic and Oceanographic Department of the Japan Coast Guard (JHOD) has been carrying out the Satellite Laser Ranging (SLR) observation at the Shimosato Hydrographic Observatory (SHO) since 1982. For 35 years, the SLR observation at the SHO contributed to a construction and a development of the International Terrestrial Reference Frame (ITRF), and also made a major contribution to an establishment of a world geodetic system as a national geodetic system in Japan in April 2002. After the major renovation between 2007 and 2009, the Shimosato station observed a crustal movement of the 2011 Tohoku-oki earthquake and continuously contributed to a global geodesy. The ranging precision (normal point RMS) maintains high accuracy of 1 - 2 cm.
In this presentation, we review a history of the SLR observation at the SHO. Our continuous SLR observation is important for a discussion to develop the future GGOS.

Acknowledgements: We acknowledge supports from NAO, JAXA, NICT, ILRS, and many associations around the world. We thank the senior staffs in the Shimosato Hydrographic Observatory for their efforts for maintenance and operation of SLR continuous observation.

*J01-1-01
Joint Symposium / J01. Monitoring of the cryosphere

Seismic Tremors and their Relation to Cryosphere Dynamics in April 2015 around the Lutzow-Holm Bay, East Antarctica

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Characteristics and statistics of seismic tremors occurring during April 2015 were investigated by using short-period and broadband seismographs deployed at Syowa Station (SYO), in the Lutzow-Holm Bay (LHB), East Antarctica. In order to examine a relationship between surface environments in particular cryosphere variation, the MODIS satellite images were utilized for comparison with the detected tremor events. Since a large volume of sea-ice was discharged during the April, together with several large icebergs passed through from the west to the east at northern edge of the fast sea-ice of LHB, it was expected to detect seismic tremors involving surrounding cryospehre dynamics. During the one month, a total number of 49 tremor events including short duratiing ice shocks were identified. Majority of the events (N=39) had their duration times more than 15 minutes, which were divided into tremors and ice shocks by the experience definition at SYO. Cryospheric sources as recorded by seismic tremors were classified into several origins (collision, calving, crevassing, crashing, etc.); "crevassing events" along the large cracks inside the fast sea-ice in LHB (04 April), "discharge events" of fast sea-ice from the Bay (07 April), "collision events" between iceberg and the edge of fast sea-ice (14 April), "crashing movement" between fragmentation of fast sea-ice and packed sea-ice (18 April), and the other origins. In particular, strong amplitude tremors with harmonic overtones were assumed to be occurred independently from whether condition, because these overtone tremors were identified at less stormy days by comparison with infrasound data at SYO.

*J01-1-02
Joint Symposium / J01. Monitoring of the cryosphere

Repetitive cryoseismicity at the Fimbulisen Ice Shelf, East Antarctica

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A source region of repetitive cryoseismic activity has been identified at the Fimbulisen ice shelf, in Dronning Maud Land, East Antarctica. The specific area is located at the outlet of the Jutulstraumen glacier, near the Kupol Moskovskij ice rise. Although the activity is mostly expressed through events of small magnitude, they are large enough to be recorded by the permanent seismic stations in the region (SNAA, TROLL, Watzmann-array), within an observation distance range between 210 and 310 km. The use of waveform cross-correlation detectors and Hidden Markov Model classifiers has provided a unique dataset extending over 13 years, from 2003 to 2016. Phases of low seismicity rates are alternating with intense activity intervals that exhibit a strong tidal modulation that is expressed in terms of event occurrence times, their geographic distribution and amplitude variation. The observed correlation follows both the neap-spring and the semi-diurnal ocean-tide cycle. These temporal characteristics of the observed cryoseismicity are approached through rate and state seismicity models with the prospects of constraining the physical mechanisms that trigger this activity and enabling the identification of the corresponding dynamic processes at work at this particular region of the Fimbulisen ice shelf.

*J01-1-03
Joint Symposium / J01. Monitoring of the cryosphere

Seismology reveals ice sheet basal conditions

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Basal conditions of the Greenland Ice Sheet (GrIS) are a key research topic in climate change studies. The recent construction of a seismic network provides a new opportunity for direct, real-time, and continuous GrIS monitoring. Here we use ambient noise surface wave data from seismic stations all over Greenland for a 4.5-year period to detect seismic velocity changes beneath the inter-station lines. We observe clear seasonal/long-term velocity changes for many station pairs, and propose a plausible mechanism for the velocity changes. The dominant factors causing these changes might be pressurization of both the GrIS and underlying crust by seasonal/long-term snow accumulation, and depressurization by ice thinning due to GrIS flow and ice mass loss. However, heterogeneity in GrIS basal conditions might impose strong regionalities on the results. An interesting feature is that, even at adjacent station pairs in the inland GrIS, both velocity decrease and increase can be caused by snow accumulations. The former pair might be located on a thawed bed that decreases velocity by increased meltwater due to pressure melting, whereas the latter pair might be located on a frozen bed that increases velocity by compaction of ice and bedrock. The results suggest that surface waves are very sensitive to the GrIS basal conditions, and further observations will contribute to a more direct and quantitative estimation of water balance in the Arctic region.

*J01-1-05
Joint Symposium / J01. Monitoring of the cryosphere

Advances in Design and Deployment of Seismic Arrays for Polar Regions

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Efforts since the 2007-2008 International Polar Years have focused on enhancing the design and deployment of seismic arrays for polar regions; including enhancements in power systems, seismometers, digitizers, and deployment logistics. These advances have resulted in seismic systems that are polar-rated, are light and small, have low power usage, deploy quickly, and thus, seismic arrays can incorporate larger numbers of seismometers.
Polar regions have been particularly challenging for seismic studies. Seismic systems must be designed to withstand cold/wet conditions, high-latitude solar limitations, extreme winds, as well as operate in remote locations with limited maintenance. In addition, the expense associated with accessing these remote locations drives the design towards minimal installation time and logistical load (i.e., size and weight), while maximizing ease-of-use in the field, in data handling, and in telemetry compatibility.
Here we review the advances made in the polar seismic arrays through the past 10 years, and the range of scientific discoveries that have resulted, focusing on the long-term science project, POLENET, and the recently funded Major Research Instrumentation project, GEOICE. Advances in system design include low-power consumption, optimizing solar systems, and advanced power/battery systems that optimize battery capacity and operational limits. The scientific projects include ice dynamics, ice shelf stability, hydrology, tectonic histories, and basic solid earth structure.

*J01-2-01
Joint Symposium / J01. Monitoring of the cryosphere

Inter-annual modulation of seasonal glacial velocity changes in the Eastern Karakorum detected by ALOS-1/2 data

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Whereas the ice sheets all over the world are receding, the glaciers in Karakoram are either stagnant or advancing, which is known as ‘Karakoram anomaly'. The surging dynamics and mass balance have been extensively studied in this area. However, in the Eastern Karakorum Range, the spatial and temporal changes in glacial velocity have been so far poorly understood. We have analyzed nearly all the available ALOS-1/2 data in this area and have examined the inter-annual modulation of five glaciers. The glaciers with size >30km, i.e. Siachen, Baltoro and Eastern tributary of Kundos, are mostly showing a considerable velocity change in their various parts, accompanying clear seasonal changes both in ALOS-1/2 data. However, this change mostly depends upon the individual glacier and is variable in space and time. On the other hand, the smaller glaciers (<30km), i.e. Singkhu, Gasherbrum and Western tributary of Kundos glaciers, are showing a slowdown in ALOS-2 data. Analysis of the local air surface temperature data at five observatories indicates that during the same season, the temperature trend in the study area is uneven and probably varies significantly between different glaciers. It can result in localized warming/cooling that can affect the availability of melt-water for an individual glacier. The excess surface melt-water at each individual glacier may undergo a variety of en/sub-glacial hydraulic and hydrological processes that are further different at each glacier. Thus, it will result in a complex velocity behavior in this region.

*J01-2-02
Joint Symposium / J01. Monitoring of the cryosphere

The influence of the Antarctic lithosphere on glacial isostatic adjustment modelling

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In the ESA Support to Science Element GOCE+Antarctica, we study the influence of the lithospheric structure on estimates of GIA. From recent geophysical, especially seismological, studies new insights on the deep structure of the Antarctic continents are available. However, the seismological models differ in resolution and do not provide a consistent image of the lithosphere. This is critical in analysing the feedback between the lithosphere and glacial loading or unloading.

To reduce such ambiguities, we combine the latest seismological models with gravity gradient data derived from the GOCE satellite mission and the recent ESA Polar Gap airborne survey. The gradients are in particular sensitive to the geometry and density variations of the main lithospheric layers, i.e. ice and sediment thickness, the Moho depth and the temperature and composition of the upper mantle. Initial results indicate that differences exist in the mode of compensation for West and East Antarctica related to different mantle properties.

The impact of an improved lithospheric model on GIA modelling is estimated by testing the sensitivity to the new temperature and density distribution and by comparing 1D and 3D viscosity models, especially in areas of low viscosity such as in the rapidly thinning Amundsen Sea sector of the West Antarctic Ice Sheet.

*J01-2-03
Joint Symposium / J01. Monitoring of the cryosphere

Geodetic studies of GIA and ice sheet changes by JARE

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The Antarctic ice sheet, which relates to the global climate changes through the sea level rise and ocean circulation, is an essential element of the Earth system for predicting the future environment changes. Thus many studies of the ice sheet changes have been conducted by means of in-situ geodetic observations, satellite observations such as satellite gravimetry and satellite altimetry as well. For these studies, one of the largest uncertainties is the effects of GIA, which, on the other hand, includes valuable information about the rheological properties of the solid Earth, because GIA is the rheological response of the solid Earth to the ice mass loading. The observational studies of the GIA effects should also contribute to investigate the inner structure of the Earth.
In view of these points, JARE (Japanese Antarctic Research Expedition) have been conducting absolute gravity measurements, GNSS and other geodetic observations at Syowa station and surrounding areas in East Antarctica. In particular, repeated absolute gravity measurements and continuous GNSS observations at Syowa station have been conducted since 1995, and these observation have revealed the temporal variations in both gravity and GNSS measurements due to the GIA. JARE also succeeded the absolute gravity measurement at Langhovde during 2011/2012 austral summer, which was the first outdoor measurement by JARE. Subsequently, JARE performed the outdoor absolute gravity measurement at Selungen, the central parts of the Sor Rondane Mts., during 2013 austral summer.
In this paper, related to the studies of GIA and ice sheet changes, we report the geodetic observations so far made by JARE, and the future plans as well.

*J01-2-04
Joint Symposium / J01. Monitoring of the cryosphere

Using geodetic data to constrain contemporary GIA signals in Scandinavia and North America

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The present-day glacial isostatic adjustment (GIA) signal in two major former glaciation centres, Scandinavia and North America, is constrained in a semi-empirical model by joint inversion of GPS-measured land deformation rates and GRACE-measured gravity changes. Both the GPS and GRACE datasets are corrected a priori for the effect of hydrological loading using the PCR-GLOBWB hydrology model, a correction which can, at least at local scales, significantly impact the fit of model predictions to the observational data. In the Scandinavian region, the GRACE trend is also corrected for present-day ice mass changes using IceSat data for the glacierized regions of Svalbard and the Russian Arctic. The observational data are combined with a suite of forward GIA model predictions which allow for variation in both ice sheet history and Earth model characteristics, with the best-fit posterior model simultaneously minimizing the misfit between both types of constraint. When only GPS data are incorporated into the prior model a good fit is obtained (X2 < 1). The result is similar when only GRACE data are used as constraint, and the best overall fit is obtained when both datasets are inverted. Within formerly glaciated regions, the method provides a realistic prediction of the uncertainty associated with the GIA process at a level that is typically ~1 order of magnitude smaller than the uncertainty associated with forward GIA models. For example, for vertical uplift rates, predicted GIA uncertainties range from ~0.2-1 mm/yr, with the largest rates present in the former load centres of the northern Gulf of Bothnia and Hudson Bay. The GIA predictions can be used in sea-level studies to better constrain the magnitude and uncertainty of the GIA contribution to regional sea-level budgets. Also assessed is the sensitivity of the model predictions to variations in ice sheet and Earth model combinations, and the ability of the method to resolve preferred values for these parameters.

*J01-2-05
Joint Symposium / J01. Monitoring of the cryosphere

5000 Year Advance and Retreat Models for West Antarctica and a Geodetically Based Solution for Mantle Viscosity and More Recent and Accelerated Cryospheric Loss

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We model the present-day time-dependent bedrock motion of Antarctica driven by deep Earth elastic and viscous-gravitational response to continent-wide glacial mass changes. During the past two decades ice mass balance assessment has been achieved using space-based imaging and surface mass balance (SMB) modelling, altimetry and SMB, and with GRACE time-varying gravity. Crustal uplift trends are only recently emerging as a reliable source of constraint from data employed in the POLENET Project using Global Positioning System (GPS) geodesy. Two other observations have also emerged in the last decade: seismic imaging on the upper mantle and transition zone, at various levels of resolution, and rough maps of the basal hydrology that reveal channels and lake activity to be rather pervasive in many part of west Antarctica. The latter two advances in our knowledge were poorly integrated into models of mantle and ice history, the two main features that control predictions of glacial isostatic adjustment (GIA) in West Antarctica. Numerous models have emerged using the seismic imaging of the shallow upper mantle to compute GIA with laterally varying viscosity. Here we present new results of a traditionally radially layered model with updated ice history and seismically informed upper mantle viscosity structure and relatively free lower mantle viscosity.

*J01-3-01
Joint Symposium / J01. Monitoring of the cryosphere

High resolution gradient fingerprint mapping and its impact on urban planning.

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Local sea level rise is a measure of several competing processes, such as the contribution of melting ice from polar ice sheets, short-term processes related to ocean and atmospheric circulation, vertical land motion, viscoelastic adjustment of the mantle and crust and intense storm flooding. Of all these components, polar ice sheets will contribute most in the near to long-term future. It is therefore paramount to understand how sensitive
local sea level is to spatio-temporally variable patterns of ice thickness in glaciated areas around the world. Here, we propose a new tool to assess this sensitivity based on gradient fingerprint mapping (GFM). This method quantifies exactly the derivative dS/dH, where S is local sea level and H ice thickness around the world. This derivative can be used to compute local projections of sea level using the following approach: S = dS/dH * DH + deltaS, where dS/dH is the gradient fingerprint (as it relates to ice) and DH any projected change in ice thickness (be it from observations extrapolated in time, or semi-empirical approaches, or model-based projections). deltaS encompasses other time variable components (assumed of a lower order) described above. Using high-resolution GFM,
urban planners can assess which glaciated areas around the world will be of relevance to sea level change at their specific location, and how to instantly transfer projections of polar ice sheet evolution into localized sea-level change projections, along with associated uncertainties.

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.

*J01-3-02
Joint Symposium / J01. Monitoring of the cryosphere

Sea level rise from the Greenland and Antarctica ice sheet melt from combined CryoSat and GRACE inversion

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The combination of space-based remote sensing data, especially gravity field changes from GRACE and elevation changes from CryoSat, may yield time series of Greenland and Antarctica mass balance with both high temporal and spatial resolution, highlighting the varying individual mass loss behaviour of major glaciers systems, while still keeping a “correct" overall ice sheet wide mass loss. Although GIA-related errors continue to be large in Antarctica, the temporal changes in mass balance are well determined, and show significant acceleration both over the Antarctic Peninsula and the Pine Island/Thwaites glacier systems. For Greenland the large yearly melt event of 2012 followed by extraordinary cool summers have meant that the Greenland ice sheet mass loss have been slightly decreasing during the CryoSat period 2010-16, with large variations between individual glaciers and ice streams.

In the presentation we outline change results from CryoSat and GRACE 2010-2016, for both Greenland and Antarctica, using models of firn compaction and density as auxillary data. We estimate an overall mass balance of Greenland around -265 GT/yr and for Antarctica -145 GT/yr, representing nearly a doubling of Antarctica mass loss since 2002, while Greenland show only relatively small overall accelerations, with large regional melt region variations. From the ice sheet melt data, we find a current global sea level rise component of 1.1 mm/yr, or about 1/3 of the currently observed global sea level rise. Sea level rise from the melting ice sheets is far from constant across the globe due to associated gravity field and loading changes, and we show estimates of the current regional “fingerprinting" of the sea level rise signal.

*J01-3-03
Joint Symposium / J01. Monitoring of the cryosphere

A 25-year Arctic Sea-level Record (1991-2016) and first look at Arctic Sea Level Budget Closure

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A new initiative within the ESA Sea Level Climate Change initiative (SL-cci) framework to improve the Arctic sea level record has been initiated as a combined effort to reprocess and retrack past altimetry to create a 25-year combined sea level record for sea level research studies. One of the objectives is to retracked ERS-2 dataset for the high latitudes based on the ALES retracking algorithm through adapting the ALES retracker for retracking of specular surfaces (leads). Secondly a reprocessing using tailored editing to Arctic Conditions will be carried out also focusing on the merging of the multi-mission data. Finally an effort is to combine physical and empirical retracked sea surface height information to derive an experimental spatio-temporal enhanced sea level product for high latitude. The first results in analysing Arctic Sea level variations on annual inter-annual scales for the 1992-2015 from a preliminar version of this dataset is presented. By including the GRACE water storage estimates and NOAA halo- and thermo-steric sea level variatios since 2002 a preliminary attempt to close the Arctic Sea level budget is presented here. Closing the Arctic sea level budget is by no mean trivial as both steric data and satellite altimetry is both sparse temporally and limited geographically.

*J01-3-05
Joint Symposium / J01. Monitoring of the cryosphere

Glacier surge mechanism of Steele Glacier in Yukon, Canada: the 2011-2016 surging episode

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Glacier surge is a periodical orders-of magnitude speed-up event during a short active phase, accompanying terminus advance and ice thickness changes. Near the border of Alaska and Yukon, Canada, there are numerous surge-type glaciers, and their behaviors has received a good deal of scientific attentions. To date, the dynamics have been examined at some surge-type glaciers, but there remain some questions about the generation mechanism.
High-quality images of recent satellites have allowed us to capture the evolutions of surging episodes with high temporal resolution. Steele Glacier in the southwest Yukon is one of the recently activated surge-type glaciers after the quiescence of ~50 years. It experienced the last surge in 1965-1967, and the peak speed was about 24 m/d in early summer 1966 (Stanley, 1969). However, the details of the surging evolution remain unclear. Here we examined the spatial and temporal changes in ice speed, ice thickness and moraines associated with the recent event for the first time in ~50 years.
We used ALOS/PALSAR, Landsat-7, Landsat-8, and Sentienl-1A images to derive the ice speed evolution between 2007 and 2016. Although we have no data in late 2011-early 2013 due to the data availability, RADARSAT-2-based velocity data (Waechter, 2013) showed the latest surge initiated in 2011, and the Sentinel-1A-based velocity data showed it terminated in fall 2016. The observed maximum speed was greater than 20 m/d in early summer 2015, whereas the quiescent speed was ~0.4 m/d between 2007 and 2011. The rapid acceleration changed the ice thickness, which is revealed by Terra/ASTER DEMs. In 2006-2011, the ice thickened above the confluence. In 2013-2016, the ice thickened in the middle and downstream region, while it thinned above the confluence.
Based on the ice thickness changes and the moraine movements, the surge started at the confluence of Hodgson and Steele Glaciers. We will discuss the surge mechanism based on the diverse datasets.

Classification of ice tremor recorded at Syowa Station in Antarctica

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Tectonic earthquakes and tremors related to ice (ice tremor) have been observed by seismic stations in Antarctica. Ice tremors are the tremors which are originates in some ice motion (Kanao et al., 2012). Purposes of this study are to classify ice tremors and to reveal the spatio-temporal variation in the distribution of ice tremors.
We use the waveform data recorded by seismometer at coastal stations. The analysis period is from January to December in 2014. We define here an ice tremor as the tremor of which P-waves and S-waves are not clear and the duration is longer than five minutes.
We find the total of 148 ice tremors in 2014. The monthly number of the ice tremors correlates well with the monthly mean temperature from April to December. We classify the ice tremors into three types based on a temporal variation in their spectrum features. Type A is the ice tremor which shows that the duration is long (about ten thousands seconds) and the amplitude is small over the waveform. Type B is that of which dominant frequency changes irregularly over the waveform. Type C is that of which dominant frequency continuously decreases and the overtone is recognized. The hypocenters of 47 ice tremors are determined in this study. There are 26 ice tremors, six in the coastal area, six on the sea area and 14 on the land area, within ˜ 150 km from the stations.
In summer, both the seismic and microbaroms amplitudes are large and the shape of the waveform of type A is excited by sea wave. In winter, the amplitude of microbaroms is large, while that of the ice tremor is not recorded well because of growing coastal ice (Grob et al, 2011). The hypocenters of type C are located on the sea area ˜ 150 km away from Syowa station. Eckstaller et al. (2006) and MacAyeal et al. (2008) reported ice tremors related to iceberg and the spectral feature of them are similar to that of type C. Therefore, we suggest that the source of the type C is related to the iceberg motion.

*J01-P-02
Joint Symposium / J01. Monitoring of the cryosphere

GROUND DEFORMATION MAPPING BY ALOS1/2 INSAR: CASE STUDIES AT HERSCHEL ISLAND, CANADA, AND BATAGAIKA CRATER, SIBERIA

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The permafrost area covers about 1/4 of the northern hemisphere and its thawing can lead to ground deformation. That ground deformation has been studied as a serious problem in the Arctic Ocean coastal area such as Russia for a long time, because the deformation causes damage to architectures at these areas. However, there have been no quantitative observation data, and the spatial and temporal distributions have hardly been investigated. On the other hand, by the recently global warming influence, the importance of organic carbon stored in permafrost is pointed out. Although the release of methane gas is confirmed in some thermokarst lakes, it is very difficult to observe the permafrost in a wide area by field study. Instead, it is technically possible to monitor the subsidence and uplift of the ground over the permafrost area, which could potentially make a significant contribution to the monitoring thawing process of permafrost.
In this study, we attempted to detect ground deformation signal in permafrost area by remote sensing using interferometric synthetic aperture radar (InSAR). Using the data of two SAR satellites ALOS and ALOS2 launched by JAXA, we observed recent ground deformation from 2007 to 2016. Focusing on the slump terrain with relatively fast fluctuation velocity as the observation target, we detected ground subsidence in Herschel Island in Canada and Batagaika Crater in Russia. In Herschel Island, we observed the subsidence and coastal erosion in recent years by ALOS2 which has not been repoted. At the Btagaika Crater, however, it is not yet certain if the detected signals really indicate subsidence, because the employed digital elevation models seem to have biases.

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Joint Symposium / J01. Monitoring of the cryosphere

Temperature dependent seismic-frequency attenuation in ice and permafrost

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There is an increasing interest in cryoseismic waves and their ability to monitor seismogenic processes and environmental conditions in the cryosphere [Podolskiy and Walter 2016]. However, laboratory work to understand and interpret this information is lacking, especially near the melting point and at seismic frequencies. For example, seismic attenuation in ice and permafrost is very sensitive to temperature, especially close to the melting point, providing the opportunity to obtain temperature profiles from seismic data, given controlled experimental attenuation databases. Peters et al. [2012] estimated englacial temperature from a seismic survey based on resonance measurements, > 100 Hz, on ice cores [Kuroiwa 1964], showing good agreement with other measured and modeled temperature profiles in the area. This technique could be improved with seismic-frequency laboratory measurements. In saline permafrost, 1 MHz P-wave attenuation was measured to increase dramatically near the eutectic temperature, suggesting a wave-induced phase change attenuation mechanism [Dou et al., 2016]. Broadband measurements and comparison to crystallization kinetics could confirm this hypothesis. We have adapted a seismic-frequency (0.1 - 100 Hz) sub-resonance apparatus [Saltiel et al., 2017] to measure shear modulus and attenuation of frozen materials under controlled temperature conditions. These measurements can be directly applied to ongoing efforts to use active and passive seismic surveys to measure englacial temperature profiles and monitor permafrost thaw. We are also pursuing laboratory experiments to contribute to our understanding and interpretation of seismic data of glacier bed sliding frictional behavior, and ice tensile/shear fracturing to constrain calving and crevassing rates. New experimental facilities make the systematic exploration of the seismic properties of frozen materials possible, which will increase the accuracy and utility of cryoseismology datasets.

*J02-1-01
Joint Symposium / J02. Recent large and destructive earthquakes

Complex seismicity and hypocenter distribution of the 2016 Kumamoto earthquakes, Kyushu, Japan, and their relation to the stress field and crustal structure

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Large earthquakes of M6.5 and M7.3 occurred in April, 2016, in the Kumamoto prefecture, Kyushu, Japan. An urgent joint seismic observation by several universities and institutes in Japan was conducted in order to investigate the detailed feature of the seismic activity.
The hypocenter of the M6.5 earthquake of April 14 locates beneath the Hinagu fault zone. While the hypocenter of the M7.3 earthquake of April 16 locates about 5km WNW of the M6.5, and beneath the Futagawa fault zone. The seismic activity was distributed along both the Futagawa and Hinagu fault zones, and the induced earthquakes were activated along the Beppu-Shimabara graben. However, detailed hypocenter distribution and the focal mechanism solutions indicate that the strike of the M6.5 fault is oblique to the trace of Hinagu fault, and that the initial rupture of the M7.3 occurred at off-fault of the Futagawa fault. In addition, the almost aftershocks did not occur at the fault plane on which the main rupture of M7.3 took place.
In this region, the high background seismicity had been observed, and M5.0 earthquake occurred in 2000. Inelastic strain distribution estimated by seismic moment tensor data implies that the source region corresponds to the relatively large strain area, which suggests the large inelastic strain created stress concentration. Although the N-S minimum principal stress is dominated in this region, the maximum and moderate principal stresses are spatially alternated. The complex fault system and seismicity could be attributed to such a uniaxial extension of deviatoric stress field.
Seismic tomography and magnetotelluric analysis show that the low velocity, moderate to high Vp/Vs ratio and conductive region exists below the large earthquakes. In addition to the stress concentration, the fluid supply from the lower crust probably trigger the large earthquakes and high-level seismicity.

Detailed crustal deformation and fault ruptures of the 2016 Kumamoto Earthquake revealed by ALOS-2 SAR data

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We report ground displacement associated with the 2016 Kumamoto Earthquake obtained by ALOS-2 SAR data. For the SAR analyses, we applied InSAR and pixel offset methods, which has successfully provided a 3D displacement field showing the widely- and locally-distributed deformation. The obtained displacement field shows clear displacement boundaries linearly along the Futagawa, the Hinagu, and the Idenokuchi faults across which the sign of displacement component turns to be opposite, suggesting that the fault ruptures reached the ground surface or subsurface. The known fault trace of the Futagawa fault terminates at the western edge of Aso caldera, but the displacement discontinuity clearly extends into the caldera with a position slightly shifting northward. Our fault model suggests that the main rupture occurred on the Futagawa fault with a right-lateral motion including a slight normal fault motion. The rupture on the Futagawa fault extends into the Aso caldera with slightly shifting the position northward. Of note, the fault plane oppositely dips toward southeast. It may be a conjugate fault against the main fault. For the Idenokuchi fault, a normal fault motion is dominant at the depth of around 5 km. The Idenokuchi faults runs near the Futagawa fault in parallel, and they have different slip components separately. It maybe suggest a slip partitioning, which supports the idea proposed by Toda et al. (2016). In the western side of the source region, the slip on the Hinagu fault, in which the Mj6.5 and Mj6.4 foreshocks occurred with a pure right-lateral motion, is also deeply involved with the main shock.

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Ground motion simulation during the 2016 Kumamoto earthquake mainshock in near-fault area and Aso caldera

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We studied the strong ground motions caused by the heterogeneous rupture process during the mainshock of the 2016 Kumamoto earthquake sequence (Mj7.3). The source rupture process was analyzed using strong motion data, assuming a fault geometry along the Hinagu and Futagawa faults in accordance with the surface ruptures. We assigned point sources densely with an interval of 0.2 km on the assumed fault planes in order to reproduce appropriately near-fault ground motions, and estimated spatiotemporal slip at control points discretized with an interval of 1.8 km on the fault planes by the multiple time-window linear waveform inversion method (e.g., Hartzell and Heaton, 1983). The rupture started at a northwest-dipping fault plane along the Hinagu fault with almost pure right-lateral strike-slip, and continuously propagated across the junction of the Hinagu and Futagawa faults. Then, it propagated northeastward along the Futagawa fault, and stopped to rupture in the western part of the Aso caldera. The significant slip with 3-5 m including normal-slip component were observed on the Futagawa fault, and shallowest part has slip ranging from 1 to 2 m, which is consistent with surface rupture distribution. Strong ground motion time histories including significant coseismic displacement along the fault-parallel direction observed at two near-fault stations (Mashiki and Nishihara) were reproduced well by this source model. Significant fault-normal displacement with continuous cracks observed in the Aso valley area could be explained as lateral ground movement induced by the strong forward directivity pulse generated associated with the rupture on the Futagawa fault. We also conducted a 3D ground motion simulations up to 1 Hz using the 3D velocity structure model JIVSM (Koketsu et al., 2012) and the finite difference method to see the effect of the source rupture process including source directivity effects on the spatial variation in strong ground motions during this event.

Simultaneous estimation of the dip angles and slip distribution on the two active faults of the 2016 Kumamoto earthquake through a weak non-linear inversion of InSAR data based on ABIC

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At the 2016 Kumamoto earthquake, surface ruptures were observed not only along the Futagawa fault, where main ruptures occurred, but also along the Hinagu fault. To estimate the slip distribution on these faults, we extend a method of non-linear inversion analysis (Fukahata and Wright 2008) to a two-faults system. With the method of Fukahata and Wright (2008) we can simultaneously determine the optimal dip angle of a fault and the slip distribution on it, based on Akaike's Bayesian Information Criterion (ABIC) by regarding the dip angle as an hyperparameter. By inverting the InSAR data with the developed method, we obtain the dip angles of the Futagawa and Hinagu faults as 61º ± 6º and 74º ± 12º, respectively. The slip on the Futagawa fault is mainly strike slip. The largest slip on it is over 5 m around the center of the model fault (130.9º in longitude) with a significant normal slip component. The slip on the Futagawa fault quickly decreases to zero beyond the intersection with the Hinagu fault. On the other hand, the slip has a local peak just inside Aso caldera, which would be a cause of severe damage in this area. A relatively larger reverse fault slip component on a deeper part around the intersection with Aso caldera suggests that something complicated happened there. The slip on the Hinagu fault is almost a pure strike slip with a peak of about 2.4 m. The developed method is useful in clarifying the slip distribution, when a complicated rupture like the Kumamoto earthquake happens in a remote area.

*J02-1-05
Joint Symposium / J02. Recent large and destructive earthquakes

Postseismic deformation of 2016 Kumamoto earthquake by the dense GNSS continuous observation

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The 2016 Kumamoto earthquake (M7.1) occurred on April 16 following the M6.5 earthquake on April 14, 2016. The maximum intensity 7 was observed in Mashiki-machi two times. These earthquakes occurred in the two active faults zone, Hinagu fault zone and Futagawa fault zone. After the occurrence earthquake activity enlarged to east from the aftershock area of the 2016 Kumamoto earthquake. Earthquake activity become high in northern region of Aso volcano and central part of Ohita prefecture. Our group started settlement of the continuous GNSS observation site in aftershock area of main shock, around Aso volcano and central Ohita prefecture in order to observe postseismic deformation and relationship between seismic activity and crustal deformation.
Twenty-one GNSS sites have been set up by April 28. There are nine sites in aftershock area, four sites in east area to Aso volcano, four sites in the central Ohita prefecture and three sites in southern part of Hinagu fault zone. Bernese GNSS Software Ver. 5.2 is used for GNSS data analysis of our newly sites together with GEONET and JMA GNSS sites in volcanoes (Aso, Kujyu and Garan-dake) in Kyushu for the period from April 15. We used CODE precise ephemerides and CODE Earth rotation parameters. The coordinates of the GNSS sites are estimated with respect to ITRF2008.
North-east displacement at the sites of western side of Hinagu fault and south-west displacement at the site of eastern side of Hinagu fault are observed. Postseismic deformation continues in January, 2017. After slip is assumed the cause of observed postseismic deformation. Fault parameters of two faults (Futagawa fault and Hinagu fault) are estimated. Fault slip on Hinagu fault is larger than that Futagawa fault. Width of two faults is 40 km and dip is 89 and 57 degree. It seems that after slip fault extend to the mantle. Long time observation of postseismic deformation is needed to separate deformation caused by after slip and response of viscoelasticity.

Comparison of macroseismic studies of two similar megathrust earthquakes in Ecuador

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The 2016 Muisne earthquake (7.8 Mw) in Ecuador was one of the most damaging events in the last 50 years in the country. This event caused 663 fatalities and total collapse of several structures in the epicentral zone. Comparing this earthquake with the megathrust event of 1942, 7.8 Mw, the main characteristics of the rupture process are recognized; however, distribution of damages are very different. In this paper a comparison of the intensities of the two mentioned events with intensity attenuation equations and ground motion to intensity conversion equations (GMICEs) is performed. A revision of the original evaluation of the 1942 earthquake is included. This comparison indicates that the seismic intensities for the 1942 event might be overestimated which could affect the general shape of the maximum intensity map. Finally, shake maps for the mainshock and two biggest aftershocks are generated using strong motion signals of the National Accelerometric Network. The latest, to observe amplification patterns due to site effects.

The 2016 Mw 7.8 Pedernales, Ecuador earthquake: aftershock sequence analysis using a minimum 1D velocity model

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On the 16th April 2016, a Mw 7.8 mega-thrust earthquake occurred in northern Ecuador, close to the city of Pedernales. The event ruptured an area of 120 x 60 km and was preceded by a Mw 4.8 foreshock, located only ~15 km south of the epicentre, and registered 10 minutes before the main event.

A few weeks after the main event a large array of instruments was deployed by a collaborative project between the Geophysical Institute of Ecuador (IGEPN), IRIS (USA), Geoazur (France) and the University of Liverpool (UK). This dense seismic network, with more than 70 stations, includes broadband, short period, strong motion and OBS instruments and is currently recording the aftershock activity of the main event.

Using data recorded both on the permanent and the recently deployed network we manually picked -with SDX- and located -with SDX and NonLinLoc- 250+ events corresponding to the aftershock sequence. P and S arrival times were used to obtain a minimum 1D velocity model. After relocate the seismicity we analysed the spatial distribution and its relation with the co-seismic slip and with previous models of inter-seismic coupling. It is possible to identify two lineations in the aftershock activity located to the north and south of the rupture. Moreover, the geodetic slip model shows that the boundaries of the maximum coseismic slip coincides with the observed lineaments in the aftershocks and with the rupture area of a previous Mw 7.8 event in 1942. This suggests that the features to the north and south may impose a barrier to rupture propagation, creating different segments in the subduction zone beneath Ecuador.

Previous activity has presented a northward-propagating series of ruptures greater than Mw 7 spaced approximately 20 years apart. An open question is therefore whether the present event is the start of a further series of large magnitude events in northern Ecuador, and whether slow slip events/creep in the south have fully accommodated the strain due to subduction.

*J02-2-03
Joint Symposium / J02. Recent large and destructive earthquakes

The 2015 Nepal earthquake: Evidence for a horizontal underthrusting of India beneath the Himalaya

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The 2016 Gorkha Nepal earthquake (Mw=7.9) is a fresh and bitter reminder of seismic potential induced by underthrusting the India subcontinent beneath the Himalaya and thus provide a rare opportunity to illuminate puzzles regarding the continental subduction and seismicity, for which we knew little as yet. Himalayan earthquakes are assumed to suddenly release elastic strain energy built up on the basal decollement, a mega-thrust fault along which the Indian plate is descending. However their growth to achieve greatness is impeded usually by complex structures on the megathrust. Here, by analysis of surface displacements observed mostly in southern Tibet with GPS geodesy, we show that coseismic slip of > 1 m in 2016 has propagated northward for 130-160 km at the base of the Himalaya, extending substantially into below southern Tibet. Our modeling reveals a shallowly-dipping plate interface that runs over a mid-crustal ramp fault assumed below the topographic front of the high Himalaya and stretches almost horizontally 15-25 km above a deep seismic reflector imaged beneath southern Tibet (known as the Main Himalayan Thrust), therefore distinguishing a mid-crustal shear zone of Indian upper crust in between which underlies a tapered accretionary wedge. Our finding sheds insight into two puzzling features in the Himalaya: why mid-crustal seismicity is absent for the continental subduction, and convergent deformation is primarily localized at its frontal thrust. In addition, the planar surface of the megathrust and its seismogenic downdip width of at least 200 km highlight a potential for generating giant earthquakes (Mw˜9) . We conclude that any model adopting a mid-crustal ramp- decollement geometry as the plate interface for India underthrusting beneath the Himalaya and Tibet should be modified.

*J02-2-04
Joint Symposium / J02. Recent large and destructive earthquakes

Is the 2013 Lushan earthquake (Mw=6.6) an independent event or a strong aftershock of the 2008 Wenchuan, China mainshock (Mw=7.9)?

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Following the 2008 Wenchuan earthquake (Mw=7.9), the 2013 Lushan strong shock (Mw=6.6) occurred again on the Longmen Shan thrust fault. Ever since the earthquake occurred, it has been a topic of hot debate on whether it is a strong aftershock of the 2008 Wenchuan earthquake or a new independent one. To this purpose, we investigated the seismogenic fault for the Lushan earthquake, and found that it is situated on the same fault system as that for the Wenchuan earthquake, and the Lushan shock ruptured one of the barriers which were left unbroken in the 2008 Wenchuan earthquake. In addition, we analyzed the statistical properties of the Wenchuan-Lushan earthquake sequence (WLES) using three established empirical laws on aftershocks. The modelling results showed that the WLES, in which the Lushan event is regarded as one of aftershocks of the Wenchuan mainshock, well satisfied three accepted statistical laws, namely the Gutenberg-Richter relation, modified Omori-Utsu law and Bath's law. At the same time, we observed that the weak and ductile materials between the hypocenters of the Wenchuan and Lushan shocks resulted in seismic gap in between, and the strong materials in the source region and special curved geometry of seismogenic fault for the Lushan event may be responsible for the approximately 5-year delay of the occurrence. In particular, the focal mechanism of the Lushan event, like most of the other strong aftershocks of the Wenchuan mainshock, is nearly thrust-type fault, suggesting the Lushan earthquake, together with other strong aftershocks, is controlled by the same stress environment. Most of all, we noticed that the Lushan event was triggered by the 2008 Wenhcuan main shock. Taken together, it is reasonable to infer that the Lushan event is a strong aftershock of the Wenchuan earthquake. Meanwhile, we propose in the paper that it is an important criterion for identification of aftershocks by means of judging whether they are triggered by the main shock.

*J02-2-05
Joint Symposium / J02. Recent large and destructive earthquakes

Coseismic deformation associated with the 2001 Ms 8.1 Kunlun earthquake from GPS and its tectonic implications

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We conducted several GPS surveys of triangulation network in the vicinity of surface rupture caused by the 2001 Kunlun Ms 8.1 earthquake, to deduce its coseismic deformation. Since we first carried out the near-filed survey in 2015, we have collected GPS data at 33 triangulation network sites, which are spreading along the surface rupture and centered in the Kusai Lake, Kokoxili, China. Due to the availability of these near-filed observations, we provided an updated set of GPS coseismic displacements, after removing the interseismic and postseismic deformation. The GPS-derived coseismic displacement filed shows that the maximum coseismic displacement is 2.412m at a site with the closest distance of ˜2km to the surface rupture.
Constrained by the GPS coseismic displacements, we used a variable slip model to further invert for the coseismic slip distribution associated with this event. The GPS-derived result is in consistent with previous studies from field measurements, high-resolution satellite images and InSAR. The largest slip occurred on the Kusai Lake segment with two obvious asperities on the whole. As a result of the existence of near-field observations, we estimated a more detailed slip pattern of these two asperities, one with smaller slip of 4˜6m extending to a deeper depth of ˜20 km and the other with larger slip of 5˜8 m to ˜10 km depth. At the eastern end of the 426-km-long rupture, the GPS data show evidence for small (<2 m) but non-zero slip, in a section of the fault where the earlier InSAR data did not show any slip. Based on our preliminary results, we can get that slip is penetrating coseismically much deeper than the typically assumed depth of the seismogenic layer. In order to verify this, we are conducting more experiments.

*J02-3-01
Joint Symposium / J02. Recent large and destructive earthquakes

Shattering a plate boundary: Complex multi-fault rupture during the 2016 Mw 7.8 Kaikoura earthquake, New Zealand

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On 14th November 2016, the northeastern South Island of New Zealand was struck by a major Mw 7.8 earthquake. The earthquake was the most powerful experienced in the region in more than 150 years. Shaking felt across the whole of New Zealand with widespread damage across much of the northern South Island and in New Zealand's capital city, Wellington. The earthquake straddled two distinct seismotectonic domains, breaking multiple faults in the predominantly strike-slip Marlborough Fault System and the contractional North Canterbury fault zones. Aftershocks continue to follow a broad NE-SW trend proximal to the Humps and Hundalee faults in the North Cantebury fault zone before stepping north, approximately following the Jordan Thrust and Kekerengu faults. Field observations, in conjunction with InSAR, GPS, and seismology reveal this to be one of the most complex earthquakes ever recorded. The rupture propagated northward for more than 170 km along both mapped and unmapped faults, before continuing offshore at its northeastern extent. The earthquake also generated a tsunami which was detected at four tide gauges along the east coast of the both the North and South Islands. Simple travel time inversion places the source of the tsunami in the coastal area ranging from just south of Kaikoura northwards to Cape Campbell. Geodetic and field observations reveal surface ruptures along at least 12 major crustal faults, extensive uplift along much of the coastline and widespread anelastic deformation including the ~8 m uplift of a fault-bounded block. While most of the deformation can be explained by crustal faulting alone, global moment tensors show a larger thrust component suggesting that the southern end of the Hikurangi may have also slipped. This complex earthquake defies many conventional assumptions about the degree to which earthquake ruptures are controlled by fault segmentation, and should motivate re-thinking of these issues in seismic hazard models.

Surface Ruptures that could have been caused by aftershocks of the 2016 Kaikoura earthquake

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Surface ruptures provide essential information for identification of causative faults, inferring earthquake source parameter scaling laws and estimation of recurrence and magnitude of future earthquakes. However, some surface ruptures are not necessarily generated coseismically by the mainshock, and instead could be caused by aftershocks. Surface ruptures on more than 10 faults have been observed after the 2016 M7.8 Kaikoura earthquake, making it one of the most complex events involving of multiple faults. In order to investigate whether some of the surface breaks are caused by aftershocks, we relocated the two M6.5 aftershocks and a few ~M6 aftershocks and determine their centroid depth as well as moment tensors. Rupture directivity of some of the aftershocks are also studied with a recently developed method of measuring the difference between centroid and hypocenter location. Preliminary results suggest that some surface ruptures could be caused by aftershocks. Accordingly, the surface breaks and ground deformation caused by the aftershocks should be taken into account when modeling rupture processes of the mainshock with geodetic or geological observations.

*J02-3-03
Joint Symposium / J02. Recent large and destructive earthquakes

Crustal deformation of the 2016 Kaikoura earthquake, New Zealand, revealed by ALOS-2

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The 2016 Kaikoura earthquake, New Zealand, occurred on 13 November 2016. We revealed the details of crustal deformation associated with the earthquake by ALOS-2 SAR data applying InSAR, a Pixel Offset method, and decomposition of these displacement data into vertical and horizontal components. Very large and extensive displacement was mainly detected around the Kekerengu Fault, the Jordan Thrust, the Hundalee Fault, and the Humps Fault Zone (e.g., more than 9 m uplift and horizontal shift around the Kekerengu Fault). We also constructed rectangular fault models with a uniform slip distribution using the 3D displacement data. The constructed fault models indicate that complicated fault motion occurred along both known active faults and also along unmapped faults. In addition to the large displacements, numerous linear discontinuities in the differential phase of InSAR images which may represent surface ruptures of several centimeters or larger were observed. These small-displacement linear surface ruptures may have been triggered by the main large fault slips.

*J02-3-04
Joint Symposium / J02. Recent large and destructive earthquakes

Complex rupture of the 2016 Kaikoura earthquake, New Zealand

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The M7.8 Kaikoura earthquake struck New Zealand on November 13, 2016 at 11:02:58, followed by a significant aftershock sequence. This was the largest event instrumentally recorded in the region. It took place in a complex tectonic environment, controlled by the subduction of the Pacific plate offshore the East coast of New Zealand and the Alpine transform fault. The seismic waveforms footprint indicates a complex rupture process. The seismic moment tensor computed by GEOFON shows a strong non-double-couple term, as also depicted by other global moment tensor catalogues, suggesting the complex rupture of one or multiple faults. Similarly, the hypocentral distribution of aftershocks appears distributed and clusters along lineaments with different orientations. The surface expression of rupture processes confirms the activation of mutiple faults with different orientations either during the main shock or the early postseismic phase. Finally, the surface deformation is characterized by a distributed uplift, but includes smaller scale anomalies, such as localized coseismic extrusion of more than 5 meters. We perform a broad seismological analysis, combining regional and teleseismic seismic data, to determine the rupture process of the main shock and tens of aftershocks. The main shock is analysed by combining InSAR, GPS and seismic data to resolve the slip distribution on a finite fault, both revealing strong rupture directivity and slip heterogeneity along the rupture area. The aftershock are investigated through a full waveform regional moment tensor inversion, revealing a combination of different rupture styles, including thrust, strike-slip and very shallow near vertical faulting, characteristic of different spatial clusters. Combining this information with the kinematic source analysis of the main shock, we propose a multiple rupture process for the Kaikoura earthquake rupture process.

*J02-3-05
Joint Symposium / J02. Recent large and destructive earthquakes

Seafloor displacement of the 13 November 2016 New Zealand earthquake estimated from tsunami waveforms and GPS data

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A large earthquake (Mw 7.8) occurred on 13 November 2016 at 11:02:56 UTC in North Canterbury, New Zealand. The earthquake initiated at 42.6925 S, 173.0221 E, and depth of 15 km beneath South Island. The earthquake has an oblique faulting mechanism and produced surface ruptures from multiple active faults. The aftershock area is 150 km long and 40 km wide and a part of it is located offshore. A large tsunami amplitude of 2.5 m was recorded at Kaikoura tide gauge and 5 cm to 50 cm were recorded at seven other tide gauges. The Kaikora tide gauge record also indicated a vertical uplift of 0.9 m. The vertical uplifts at KAIK and CMBL GPS stations which are located near the coast and within the source area are 0.4 and 1 m, respectively.
In this study, we used tsunami waveforms at four tide gauges (Castle point, Wellington, Kaikoura, and Christchurch) and the uplift data to estimate the seafloor displacement. We distributed 72 (18 x 4) B-spline function unit sources with spatial distance of 10 km. The resolution test show that the dataset can resolve well the displacement with 20 km of spatial variation anywhere in the offshore but the displacement with 10 km spatial variation can be resolved around the Kaikoura station.
The earthquake produced two distinct uplift regions within the aftershock area. The first region is located immediately northeast of Kaikoura and the second region is centered at approximately 70 km northeast of Kaikoura. Both seafloor uplift regions are peaked at about 1 m, and the uplift tends to become gradually smaller from the shoreline toward offshore. We interpreted that this displacement is generated by the combination of multiple active faults and an underlying thrust fault ruptures. Tsunami simulation produced tsunami amplitudes of more than 0.5 m along 200 km coastline and the maximum tsunami amplitude is 3 m. The tsunami propagation model shows that oscillation of water body occurred locally near the coastline within the tsunami source area.

*J02-4-01
Joint Symposium / J02. Recent large and destructive earthquakes

Postseismic deformation following the 2016 Mw 7.8 Kaikoura earthquake, New Zealand.

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The November 14 2016 Mw 7.8 Kaikoura earthquake in New Zealand ruptured at least 12 major crustal faults and caused widespread damage across the northern South Island. In response to the earthquake several new continuous and semi continuous GPS stations were installed in the region to augment the GeoNet CGPS network. In addition, InSAR data acquired by ALOS-2 and Sentinel-1A/B, which are acquired every 6-12 days, are used to measure post-seismic deformation across the region.

We will present the first few months of the postseismic deformation following the Kaikoura earthquake. The most rapid early postseismic deformation is observed in the region of Cape Campbell, coinciding with a large cluster of aftershocks, with about 24 cm NE motion and 26 cm uplift observed at CGPS site CMBL by the end of 2016. Sites NW of Cape Campbell have a similar NE trend and uplift with decreasing rate NW from the Needles fault. Coastal sites, south of the Clarence fault move in a more easterly direction, with the site KAIK moving 8.5 cm ESE and insignificant vertical change.

A simple postseismic deformation model based on the best-fit coseismic fault planes and assuming a 30-km-thick elastic layer overlying a Maxwell viscoelastic mantle is able to broadly reproduce the direction of postseismic deflections from north to south, but predicts maximum displacements too far inland. Adding in the dipping Pacific plate slab as an elastic body reduces the magnitude of postseismic displacement in the model but does not change directions or the location of maximum displacements significantly. We also undertake time-dependent inversions of the afterslip, solving for slip on the crustal faults that ruptured in the earthquake, as well as the underlying subduction interface. The best-fit postseismic models have afterslip on the crustal faults that ruptured in the earthquake, as well as on the subduction interface beneath the northern South Island, in addition to a component of mantle relaxation.

Intraslab rupture triggering megathrust rupture co-seismically in the December 17, 2016 Solomon Islands Mw 7.9 earthquake

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The December 17, 2016 Solomon Islands earthquake (Mw 7.9) initiated near 103 km deep in the subducting Solomon Sea slab near the junction of the Solomon Islands and New Britain trenches. Most aftershocks are located near the Solomon Islands plate boundary megathrust west of Bougainville, where previous large interplate thrust faulting earthquakes occurred in 1995 (Mw 7.7) and 1971 (Mw 8.0). Teleseismic body wave modeling and aftershock relocations indicate that the initial 30 s of the 2016 rupture occurred over depths of 90 to 120 km on an intraslab fault dipping ~30 deg to the southwest, almost perpendicular to the dipping slab interface. The next 50 s of rupture took place at depths of 32 to 47 km in the deeper (Domain C) portion of the overlying megathrust fault dipping ~35 deg to the northeast. High susceptibility to triggering in the region accounts for this compound rupture of two separate fault planes.

*J02-4-03
Joint Symposium / J02. Recent large and destructive earthquakes

Anatomy of the source zones of large earthquakes in Japan

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We use high-resolution seismic tomography to study the detailed 3-D structure in the source zones of large earthquakes in Japan to clarify their causal mechanisms. To image the Tohoku megathrust zone, we collected a large number of arrival-time data of suboceanic events (M 3.5-6.0) in the Tohoku forearc under the Pacific Ocean. The suboceanic events are relocated precisely using local arrival times of P and S waves and sP depth phase, and many outer-rise events near the Japan Trench were located by a portable OBS network. Then we inverted the arrival-time data to determine tomographic images of the megathrust zone beneath the Tohoku forearc. The obtained Vp and Vs images are similar to each other, and they show significant velocity variations in the megathrust zone. The 2011 Tohoku megathrust earthquake (Mw 9.0) and its major foreshocks and aftershocks (M > 6.0) occurred in high-velocity (high-V) areas of the megathrust zone, which may represent rigid asperities where the subducting Pacific plate and the overriding Okhotsk plate were strongly coupled. A prominent high-V area with large coseismic slip extends from the Tohoku mainshock hypocenter to the Japan Trench, which may represent the mainshock asperity. We also determined detailed tomographic images in the source zone of the 2011 Iwaki crustal earthquake (M 7.0) and the Fukushima nuclear power plant (FNPP) area. Prominent low-velocity and high Poisson's ratio zones are revealed beneath the Iwaki source area and the FNPP, which may reflect fluids released from the dehydration of the subducting Pacific slab. Our results suggest that the Iwaki earthquake was triggered by the ascending fluids from the Pacific slab dehydration and the stress variation induced by the 2011 Tohoku mainshock. The similar structures beneath the Iwaki source area and the FNPP suggest that the security of the FNPP site should be strengthened to withstand potential large earthquakes in the future.

*J02-4-04
Joint Symposium / J02. Recent large and destructive earthquakes

From Sumatra 2004 to Today, through Tohoku-Oki 2011: what we learn about Tsunami detection by ionospheric sounding.

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The tsunamigenic Tohoku earthquake (2011) strongly affirms, after the 26 December 2004, the necessity to open new paradigms in oceanic monitoring. Detection of ionospheric anomalies following the Sumatra event demonstrated that ionosphere is sensitive to earthquake and tsunami propagation: ground and oceanic vertical displacement induces acoustic-gravity waves propagating within the neutral atmosphere and detectable in the ionosphere. Observations supported by modelling proved that tsunamigenic ionospheric anomalies are deterministic and reproducible. Tsunami signature in the ionosphere is routinely detected and we show here perturbations of total electron content (TEC) measured by GPS and following tsunamigenic eartquakes from 2004 to 2011, nominally, Sumatra (26 December, 2004 and 12 September, 2007), Chile (14 November, 2007), Samoa (29 September, 2009) and the Tohoku-Oki (11 Mars, 2011). Additionally, new exciting measurements in the far-field were performed by Airglow measurement in Hawaii, showing IGWs induced by the Tohoku tsunami in the Pacific Ocean, as well as by two new recent tsunamis: the Queen Charlotte (27 October, 2013, Mw 7,7) and Chili (16 September, 2015, Mw 8.2). The detection of those two new events strongly confirms the potential interest and perspective of the tsunami monitoring by airglow camera, ground-located or potentially onboard on satellite. Observations close to the epicenter, performed by GPS networks located in Sumatra, Chile and Japan, highlight the first TEC perturbation observed within the first 10min after the seismic rupture. This perturbation contains informations about the ground displacement, as well as the consequent sea surface displacement resulting in the tsunami. In this talk we present all this new observations in the ionosphere and we discuss, under the light of modelling, the potential role of ionospheric sounding in the oceanic monitoring and future tsunami warning system.
Works presented here @ www.ipgp.fr/˜ninto

*J02-4-05
Joint Symposium / J02. Recent large and destructive earthquakes

Linking Oceanic Tsunamis and Geodetic Gravity Changes of Large Earthquakes

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Large earthquakes at subduction zones usually generate tsunamis and coseismic gravity changes. These two independent oceanic and geodetic signatures of earthquakes can be observed individually by modern geophysical observational networks. The Gravity Recovery and Climate Experiment (GRACE) twin-satellites can detect gravity changes induced by large earthquakes, while altimetry satellites and Deep-Ocean Assessment and Reporting of Tsunamis (DART) buoys can observe resultant tsunamis. In this study, we introduce a method to connect the oceanic tsunami measurements with the geodetic gravity observations, and apply it to the 2004 Sumatra Mw 9.2 earthquake, the 2010 Maule Mw 8.8 earthquake and the 2011 Tohoku Mw 9.0 Earthquake. Our results indicate consistent agreement between these two independent measurements. Since seafloor displacement is still the largest puzzle in assessing tsunami hazards and its formation mechanism, our study demonstrates a new approach to utilizing these two kinds of measurements for better understanding of large earthquakes and tsunami

*J02-4-06
Joint Symposium / J02. Recent large and destructive earthquakes

Postseismic gravity changes caused by viscoelastic relaxation after recent great earthquakes since 2004

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GRACE detected regional-scale coseismic and postseismic gravity changes after recent great earthquakes, including 2004 Sumatra-Andaman, 2005 Nias, 2006/2007 Kuril, 2007 Bengkulu, 2009 Samoa-Toga, 2010 Maule, 2011 Tohoku-Oki, 2012 Wharton Basin (Indian Ocean), and 2013 Okhotsk earthquakes. Those earthquakes caused abrupt changes in the Earth's gravity field and triggered gradual postseismic adjustment expected to continue for years to decades by viscoelastic relaxation. Significant postseismic gravity changes were recorded in GRACE by not only megathrust ruptures (as large as Mw9.2), but also earthquakes (as small as Mw8.1) with very different mechanisms, such as strike-slip earthquakes and normal faulting events. The cumulative postseismic gravity changes can be even larger than the coseismic changes depending on the rupture mechanism and the Earth's rheological structure around the region. For example, the results from the GRACE Level-2 data found that the combined coseismic gravimetric signal from Mw8.3 Kuril thrust and Mw8.1 normal faulting events (doublet) was too small to be distinguished by GRACE, but it produced substantial postseismic gravity change, indicating the prominent influence of viscous asthenosphere underlying the thin elastic lithosphere in the Kuril trench. The similar results were also found after the 2009 Samoa-Tonga earthquake doublet. We have an opportunity to examine the Earth's deformations from various types of earthquakes at time-scales from months to decades comprehensively using nearly 15 years of continuous gravity measurements from GRACE and to be extended for another decade or longer by GRACE-FO. In this presentation, we review the GRACE observations of gravity changes from those earthquakes and provide the numerical modelling results of gravity change predominantly by viscoelastic relaxation. We will show the regional variability in the rheological structures along different plate boundaries.

Fault source model for the 2016 Kumamoto earthquake sequence based on ALOS-2/PALSAR-2 pixel-offset data: evidence for dynamic slip partitioning

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Series of earthquakes including three Mw > 6 earthquakes occurred in Kumamoto prefecture in the middle of the Kyushu island, Japan. In order to reveal the associated crustal deformation signals, we applied offset tracking technique to ALOS-2/PALSAR-2 data covering three Mw > 6 earthquakes and derived the 3D displacements around the epicenters. We could identify three NE–SW trending displacement discontinuities in the 3D displacements that were consistent with the surface location of Futagawa and Hinagu fault system. We set three-segment fault model whose positions matched the displacement discontinuities, and estimated the slip distributions on each segment from the observed pixel-offset data. Whereas right-lateral slip was dominant in the shallower depth of the larger segments, normal fault slip was more significant at a greater depth of the other segment. The inferred configuration and slip distribution of each segment suggest that slip partitioning under oblique extension stress regime took place during the 2016 Kumamoto earthquake sequence. Moreover, given the consistent focal mechanisms derived from both the slip distribution model and seismology, the significant non-double couple components in the focal mechanism of the main shock are due to simultaneous ruptures of both strike-slip and normal faulting at the distinct segments.

Crustal deformation of the 2016 Kumamoto earthquake sequence (1) - Foreshocks -

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We will show the crustal deformation and the fault models obtained from SAR (ALOS-2) and Kinematic-GPS observations for the 2016 Kumamoto earthquake foreshocks that occurred on Apr. 14th and 15th, 2016 with a Japan Meteorological Agency (JMA) magnitude (Mj) of 6.5 and 6.4, respectively.

SAR: By applying conventional InSAR and MAI techniques, ground displacements have been successfully mapped. The most concentrated crustal deformation is located on the western side of the Hinagu fault zone. A locally distributed displacement which appears along the strike of the Futagawa fault can be identified in and around Mashiki town, suggesting that a different local fault slip also contributed toward foreshocks. Distributed slip models show right-lateral fault motion on a plane dipping west by 80 deg for the Hinagu fault and normal fault motion on a plane dipping south by 70 deg for the local fault beneath Mashiki town. The slip in the north significantly extends down to around 10 km depth, while in the south the slip is concentrated near the ground surface, perhaps corresponding to the Mj 6.5 and the Mj 6.4 events, respectively.

Kinematic-GPS: InSAR data cannot further separate the individual crustal deformation due to its temporal resolution. In this context, we processed Kinematic-GPS data and successfully exploited the individual coseismic displcaements for the two events. The constructed fault models show that the Mj6.5 event is located around the junction of the Futagawa fault and the Hinagu fault, while the Mj6.4 is located in the south of the Mj6.5 event. This analysis result demonstrates that Kinematic-GPS data can contribute to derive the individual source properties for the two events that occurred temporarily close to each other within a day.

Acknowledgements: ALOS-2 data were provided from the Earthquake Working Group under a cooperative research contract with JAXA (Japan Aerospace Exploration Agency). The ownership of ALOS-2 data belongs to JAXA.

Crustal deformation of the 2016 Kumamoto earthquake sequence (2) - Mainshock -

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Coseismic deformation derived from the 2016 Kumamoto Earthquake sequence was observed by GNSS stations of the permanent GNSS Earth Observation Network system (GEONET) and ALOS-2/PALSAR-2 SAR analysis. We will introduce the crustal deformation and estimated fault model of the Kumamoto earthquake mainshock that occured on Apr. 16th, 2016 with a Japan Meteorological Agency (JMA) magnitude (Mj) of 7.3.
Clear coseismic displacements due to the Kumamoto earthquake were observed by GEONET. NE displacement of 75 cm and subsidence of 20 cm was detected at the Kumamoto observation station, which is located on the north side of the Futagawa fault. On the south side of the fault, SW displacement of 97 cm and uplift of 28 cm was detected at the Choyo stations.
We have also successfully detected distributed ground displacements for the Kumamoto Earthquake by applying a SAR interferometry, MAI and Pixel Offset analysis of ALOS-2 data. The obtained displacement field shows clear displacement boundaries linearly along the Futagawa, the Hinagu, and the Denokuchi faults across which the sign of displacement component turns to be opposite, suggesting that the fault ruptures occurred there.
We invert the InSAR results with GNSS data to construct a fault model of the earthquake. Our fault model for the main shock suggests that the main rupture occurred on the Futagawa fault with a right-lateral motion including a slight normal fault motion. Due to the normal faulting movement, the northern side of the active fault subsides with approximately 2 m. The rupture on the Futagawa fault extends into the Aso caldera with slightly shifting the position northward. Of note, the fault plane oppositely dips toward southeast. It may be a conjugate fault against the mainly-slipped fault.

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The PALSAR-2 data obtained by the ALOS-2 were provided by the Japan Aerospace Exploration Agency (JAXA) through the Agreement between GSI and JAXA. The ownership of PALSAR-2 data belongs to JAXA.

*J02-P-04
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Crustal deformation of the 2016 Kumamoto earthquake sequence (3) - Small displacement linear surface ruptures detected by ALOS-2 SAR -

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We constructed and analyzed the ground surface displacement associated with the 2016 Kumamoto earthquake sequence using satellite radar interferometry images of the Advanced Land Observing Satellite 2. The radar interferogram generally shows elastic deformation caused by the main earthquakes but many other linear discontinuities showing displacement are also found. Approximately 230 lineaments are identified, some of which coincide with the positions of known active faults, such as the main earthquake faults belonging to the Futagawa and Hinagu fault zones and other minor faults; however, there are much fewer known active faults than lineaments. In each area, the lineaments have a similar direction and displacement to each other, therefore, they can be divided into several groups based on location and major features. Since the direction of the lineaments coincides with that of known active faults or their conjugate faults, the cause of the lineaments must be related to the tectonic stress field of this region. The lineaments are classified into the following two categories: (1) main earthquake faults and their branched sub-faults; and (2) secondary faults that are not directly related to the main earthquake but whose slip was probably triggered by the main earthquake or aftershocks.

Relationship between subsurface structure and large-scale fissures in the northwestern region in Aso valley caused by the 2016 Kumamoto earthquake

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In accompanied with the 2016 Kumamoto earthquake, fissures with the length and the height a few hundred meters and two meters, respectively, emerged in Aso valley (inside the Aso caldera). In this area, the top layer consists of sediments in the caldera lake created by Aso-4 eruption with the thickness a few tens of meters. InSAR and seismic data show that the region with the size of 1-4 square meter moved 1-2 m northward horizontally during strong motion of the mainshock (Fujiwara et al., 2016; Doi et al., 2016). We investigated the mechanism of the movement of these regions by estimating subsurface structure beneath this area.
Two station spatial auto-correlation (2ST-SPAC) method (Hayashi and Craig, 2016) was applied to estimate subsurface structure using ambient noises. We succeeded to estimate the S-wave velocity structure to the depth of 130 m in and around the regions with fissures. In the regions where large scale fissures were developed, a layer with S-wave velocity less than 150 m/s lay from the surface to the depth of 60 m, followed by two layers with 250 m/s and 300 m/s at depths of 60-90 m and 90-130 m, respectively. This low-velocity layer was considered to represent soft sediments in the caldera lake due to Aso-4 eruption and consistent with the nearby boring profile. Two relatively higher layers might correspond to lava layers after Aso-4 eruption. Moreover, the S-wave velocity at the top surface to the depth of 5 m was so slow as 80 m/s. We continue to estimate the distribution of the soft sediments and lava structure beneath them, to elucidate how fissures were generated in this area.

*J02-P-06
Joint Symposium / J02. Recent large and destructive earthquakes

New Guidelines for the Seismic Forecast Information after Big Earthquakes in Japan

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A big earthquake of M6.5 occurred at 21:26 on 14 April, 2016 (JST) in Kumamoto Prefecture. That was the beginning of “The 2016 Kumamoto Earthquake". Japan Meteorological Agency (JMA) issued information about aftershock probability after 18 hours of this earthquake. However, after 28 hours of the M6.5 earthquake, a bigger earthquake of M7.3 occurred in the same region and triggered distant earthquakes. The seismically active area was finally spread up to about 150km long. As this seismic activity was revealed that it was not a simple mainshock - aftershock patterns, JMA stopped issuance of the following information about aftershock probability. With lessons learned from this, seismologists and JMA discussed under a framework of the Headquarters of Earthquake Research Promotion (HERP), and new guidelines were published in August 2016. The points of the guidelines are followings.
(1)JMA calls attention to strong motion which is similar level to the first big earthquake for about one week after big earthquakes.
(2)If there were prior cases of foreshock - mainshock - aftershock series or earthquakes with similar magnitude which occurred in the short term near the big earthquakes, JMA calls attention to such cases.
(3)If active faults and assumed source regions of big thrust-type subduction-zone earthquakes existed near the big earthquakes, JMA explains the characteristics and calls attention to them.
(4)After one week, if the active seismic activity continues, JMA issues aftershock probability. The probability is shown by magnification ratio which compares to the probability just after the biggest earthquake and before the big earthquakes.
(5)JMA uses a word “earthquake" instead of “aftershock" when JMA calls to attention to strong motion by aftershocks, because the word of “aftershock" gave some impression to people that bigger earthquakes would not occur.
We will introduce new Japanese policy and actual examples about Seismic Forecast Information after big earthquakes.

*J02-P-07
Joint Symposium / J02. Recent large and destructive earthquakes

Characterized Source Model of 2016 Meinong Earthquake, Taiwan, Inferred by the Empirical Green's Function Method

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We investigate the source characteristics of the 2016 (ML6.6) Meinong earthquake, which strongly struck the southwest Taiwan on 2016/02/06 03:57:26 (local time), by strong motion simulation with the Empirical Green's Function Method (EGFM).This event induced a noticeable amount of building damage reported due to the strong ground motion, especially two high-rise buildings collapsed in Tainan City and caused totally 117 deaths and more than 500 casualties. Several source models of the 2016 Meinong earthquake inverted by strong motion, teleseismic and GPS data were proposed from various studies. Most of them show two asperities on the east –west trending fault plane. In this study, we focus on the characterized source model (CSM), which includes one or more rectangular Strong Motion Generation Areas (SMGAs) on a presumed fault plane. The CSM can be derived by implementing EGFM using small-event records as the empirical Green's functions. An optimal CSM will be derived by fitting the synthetics to the observed waveforms. The CSMs can be utilized conveniently for inputs of a source model to predict strong ground motions for earthquake scenarios in addressing the seismic hazard. Thus, validation of CSM for a specific earthquake will benefit the reliability of predicting source model. For a seismically active region like Taiwan, it is important to perform ground-motion-simulation cases for moderate-to-large events to obtain an empirical relationship for addressing CSMs. Then, shaking maps from strong motion simulations for specific fault scenarios can be useful for seismic disaster preparation plan.

*J02-P-08
Joint Symposium / J02. Recent large and destructive earthquakes

Slip Distribution of the 2015 Lefkada Earthquake and its Implications for Fault Segmentation

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It is widely accepted that fault segmentation limits earthquake rupture propagations and therefore earthquake size. While along-strike segmentation of continental strike-slip faults is well observed, direct evidence for segmentation of off-shore strike-slip faults is rare. A comparison of rupture behaviors in multiple earthquakes might help reveal the characteristics of fault segmentation. In this work, we study the 2015 Lefkada earthquake, which ruptured a major active strike slip fault offshore Lefkada Island, Greece. We report ground deformation mainly on the Lefkada Island measured by interferometric synthetic radar (InSAR), and infer a coseismic distributed slip model. To investigate how the fault location affects the inferred displacement based on our InSAR observations, we conduct a suite of inversions by taking various fault location from different studies as a prior. The result of these test inversions suggests that the Lefkada fault trace is located just offshore Lefkada Island. Our preferred model shows that the 2015 earthquake main slip patches are confined to shallow depth (< 10 km), with a maximum slip of ~1.6 m. In comparison to the 2003 earthquake, which mainly ruptured the northern part of the Lefkada fault, we suggest that the 2015 earthquake closed the seismic gap, at least partially, left by the 2003 earthquake by rupturing the shallow part of the Lefkada fault. The spatial variation in slip distributions for the two earthquakes reveals segmentation along strike, and possibly downdip of the Lefkada fault. A comparison of aftershock locations and coseismic slip distribution shows that most aftershocks appear near the edge of main coseismic slip patches.

*J02-P-09
Joint Symposium / J02. Recent large and destructive earthquakes

Characterized source model for estimating strong ground motions during 2016 Tottori-ken Chubu Earthquake

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Strong ground motions from the 2016 Tottori-ken Chubu earthquake (Mw6.2) struck in Kurayoshi city, Tottori prefecture, on Japan Sea side, on October 21, 2016. PGA of 1494 gal was observed at TTR005 (Kurayoshi,epicentral distance: 6km) station. We estimated the characterized source model, which explain broad-band strong motions, during this earthquake based on the results of the waveform inversion using the strong motion data and the empirical Green's function method.
First, we analyzed the slip distribution during this earthquake using the multi-time window linear waveform inversion method (Sekiguchi et al., 2000). Target frequency range is 0.1-1.0Hz. As a result, large slip area was constructed round the hypocenter. Seismic moment of the estimated model is 2.0*10^18Nm.
Next, the characterized source model was constructed based on the slip distribution from the waveform inversion. We extracted asperity from the slip distribution and high rate area (HRA) from the moment rate distribution by the criterion of Somerville et al. (1999). The area and location of the asperity and the HRA are estimated to be nearly the same.
Finally, we analyzed the SMGA model using the empirical Green's function method (Irikura, 1986). We attempted to examine whether the strong ground motions at TTR005 located very near the fault plane are simulated. Target frequency range is 0.3-10.0Hz. As a result, the location of the SMGA is nearly the same as the estimated large slip area from the waveform inversion results. The scaling relationship SMGA area versus seismic moment is consistent with on that of combined area of asperities versus seismic moment by the previous study (Irikura and Miyake, 2001). The asperity, the HRA and the SMGA of this earthquake are collocated with nearly the same area.

*J02-P-10
Joint Symposium / J02. Recent large and destructive earthquakes

Changes of S-wave velocity and polarization anisotropy associated with the 2011 Tohoku Earthquake detected by the observation of the seismic ACROSS signals

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We analyzed the seismic ACROSS (Accurately Controlled, Routinely Operated , Signal System) signals using the data of the borehole observation network of Tono Research Institute Earthquake Science (TRIES) and detected clearly changes of S-wave velocity and polarization anisotropy associated with the 2011 off the Pacific coast of Tohoku Earthquake (March 11, 2011 Mw 9.0, hereinafter called Tohoku Earthquake) in Tono area of epicentral distance approximately 600km, located in the southwest Japan. Seismometers and strain meters or stress meters at the borehole stations are installed in the Toki granite at a depth of 110m - 1030m, whose direct distance from the seismic ACROSS transmitter (the Toki station) to seismometers are 210m - 8.5km. We estimated daily changes of the direct S-wave travel times by the cross spectrum method for two years from April, 2010 to March, 2012. Coseismic travel time delays of the direct S-waves associated with the Tohoku Earthquake were 0.3 - 7.3ms, and the detailed processes to gradually recover to the original travel times over a year were observed. Coseismic decreases in S-wave apparent velocity were 0.2 - 0.6%, and decreases of the velocity observed by stations in the southeastern direction from the transmitter were remarkable. At these stations, changes of the S-wave polarization anisotropy that the SH-wave velocities were decreased considerably in comparison with the SV-wave were observed. The crust in this area was elongated in direction of NE-SW to NNE-SSW with the change in the order of 10e-6 strain or 10kPa associated with the Tohoku Earthquake. As a result, the S-wave velocity decreased due to the opening of cracks in the rock. Vertical (high angle) cracks in the WNW - ESE and NW - SE direction were opened, so that the SH-wave propagated in NE direction was considerably delayed in comparison with the SV-wave.

A coupled model of stress-driven frictional afterslip and viscoelastic relaxation following the 2011 Tohoku-oki earthquake

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Postseismic deformation following the 2011 Mw9.0 Tohoku-oki earthquake has been captured by both on-land GNSS and seafloor GPS/Acoustic networks. Previous studies have shown that the observed postseismic displacements can be reproduced as a sum of contributions from viscoelastic relaxation of coseismic stress changes in the upper mantle and afterslip on the plate interface surrounding the coseismic rupture. In most previous studies, viscoelastic relaxation and afterslip were modeled separately and afterslip was estimated kinematically. In this study, we develop a three-dimensional coupled model of stress-driven frictional afterslip and viscoelastic stress relaxation in order to investigate the frictional properties on the plate interface, upper mantle rheology, and the relative contributions of the viscoelastic relaxation and afterslip to the overall postseismic deformation following the 2011 Tohoku-oki earthquake.

We assume that afterslip is governed by a rate-strengthening friction law that is characterized with a friction parameter (a-b)*sigma. Viscoelastic relaxation of the upper mantle is modeled with a biviscous Burgers rheology that is characterized with the steady-state and transient viscosities. We calculate the evolution of afterslip and viscoelastic relaxation using an assumed coseismic slip model as the initial condition.

We examine the effects of the friction parameters, mantle viscosities, elastic thickness of the slab and upper plate, and coseismic slip distribution on the model prediction and explore the range of the parameters that can fit the observed postseismic displacements. We also examine if afterslip overlaps regions that ruptured seismically during M6.3-7.2 earthquakes from 2003 to 2010. We find that significant overlap between afterslip and the historical M6.3-7.2 coseismic rupture areas are required to fit the horizontal displacements.

Tidal triggering of earthquakes after the 2011 Tohoku earthquake

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I investigated correlations between tides and earthquakes off the Pacific coast of eastern Japan for about five years after the 2011 Tohoku earthquake (Mw 9.1). A previous study has shown a high correlation in the northern part of the focal area of the Tohoku earthquake, where the mainshock rupture initiated, in about ten years prior to the Tohoku earthquake (Tanaka, 2012). The data I used are the Global Centroid Moment Tensor (CMT) solutions of shallow earthquakes (H < 70 km) with Mw 5.0 or larger for the period from 1976 to 2015. For each event, I calculated tidal shear stresses on the fault plane (Tanaka et al., 2002), and assigned a tidal phase angle at the time of occurrence. Based on the distribution of tidal phase angles, I tested whether they concentrate near some particular angle or not by using the Schuster's test (Schuster, 1897). In this test, the result is evaluated by p-value, which represents the significance level to reject the null hypothesis that the earthquakes occur randomly irrespective of tidal phase angle. After the Tohoku earthquake, no significant correlation was found in the area where a high correlation was found before the Tohoku earthquake. The p-values in this area are larger than 10% in the period of about five years after the Tohoku earthquake. On the other hand, small p-values were observed on the northwest side of the large slip area of the Tohoku mainshock. A small p-value of 2.8% was obtained in the area near the coast, where large postseismic afterslip has been identified by geodetic measurements (Sun et al., 2014; Iinuma et al., 2016). In this region, no significant correlation was found for about 35 years prior to the Tohoku earthquake. The p-value was smallest (1.6%) just after the Tohoku earthquake, and gradually increased with time. This behavior seems to be correlated with time evolution of afterslip which shows rapid decay over time (Ozawa et al., 2012).

*J02-P-13
Joint Symposium / J02. Recent large and destructive earthquakes

The ISC Event Bibliography: an update

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Researches studying specific earthquakes and/or seismic events in general are often required to do time consuming searches in order to retrieve the literature concerning the events of their interest. To facilitate this task, in 2012 the International Seismological Centre (ISC) launched a new service, the ISC Event Bibliography (Di Giacomo et al., 2014), that allows users to do interactive searches (www.isc.ac.uk/event_bibliography/bibsearch.php) of scientific articles based on event parameters and, optionally, publication metrics (e.g., journal, author, year of publication etc.). The journals included in our database are not limited to seismology but bring together a variety of geoscience fields (e.g., engineering seismology, geodesy and remote sensing, tectonophysics, monitoring research, tsunami, geology, geochemistry, hydrogeology, atmospheric sciences, etc.) making this service useful also in multidisciplinary studies. Usually papers dealing with large data set are not included (e.g., papers describing a seismic catalogue). Some of the most notable earthquakes are the subject of several hundreds of articles published over a period of few years. Currently the ISC Event Bibliography includes over 18,000 individual publications from about 500 titles related to over 15,000 events that occurred in last 100+ years. The bibliographic records in the Event Bibliography start beginning of last century, and it is updated as new publications become available, and with this contribution we intend to show the usefulness of the ISC Event Bibliography considering recent large events.

*J02-P-14
Joint Symposium / J02. Recent large and destructive earthquakes

The seismotectonic implications of source models of M-7 class earthquakes before ad after the 2011 Tohoku-Oki Earthquake using offshore tsunami records

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Some major (M ˜7) earthquakes occurred in and around the rupture area of the 2011 Tohoku-Oki Earthquake. In this study, we investigated their source models using offshore tsunami records and discussed their relationships with the mainshock, which will give us new implications for subduction zone tectonics.
On March 9, 2011, Mw 7.2 and 6.6 interplate earthquakes preceded the mainshock at ˜ 30 km northeast from the mainshock epicenter. The rupture area of the Mw 7.2 event was complementary to its postseismic slip area and to the epicenters of smaller seismicity before the mainshock. After the Mw 6.6 event, one of the aftershocks of the Mw 7.2, seismicity abruptly expanded to the area next to the mainshock epicenter. This migration of seismicity after the Mw 7.2 earthquake suggests the occurrence of the cascading propagation of the major earthquakes and aseismic slip towards the mainshock epicenter, which was likely to trigger the mainshock.
After the mainshock, some intraslab earthquakes occurred near the Japan Trench, associated with the slab bending stress perturbed by the 2011 mainshock. Based on a finite fault modeling of the intraslab doublet earthquake on Dec. 12, 2012, the shallow normal-faulting sub-event (Mw 7.2) extends down to ˜ 35 – 40 km whereas the top of the deep thrust-faulting sub-event (Mw 7.2) was estimated at ˜ 45 – 50 km, indicating an obvious deepening of the intraslab seismicity after the mainshock. The change is interpreted as the results of static stress change and of reduction of shear strength in the slab. Meanwhile, an intraslab strike-slip earthquake (Mw 7.0) in 2011 beneath the landward slope of the Japan Trench happened within the shallow portion of the slab under the downdip extensional field and its fault did not expand below the stress neutral depth estimated by the pre-2011 seismicity. This suggests that the enhancement of the downdip tensional stress after the mainshock was not large as compared to the near-trench area.

*J03-1-01
Joint Symposium / J03. Deformation of the lithosphere: Integrating seismology and ge odesy through modelling

Pre-, Co-, and Post-seismic deformation of the 2016 Oct 21th M 6.6 Central Tottori earthquake

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There is a zone of active microseismicity along the Japan Sea coast in the San'in region, southwest Japan. Some large earthquakes including the 1943 M7.2 Tottori and the 2000 M7.3 western Tottori earthquakes also occurred in this seismic zone. Nishimura et al.(2014) showed a zone of high strain rate observed by GNSS almost overlapped the seismic zone and proposed to call it “the San'in shear zone".

We constructed 13 continuous GNSS stations in late 2014 so as to clarify a detailed distribution of the San'in shear zone. These stations constitute three linear arrays across the shear zone. An M 6.6 earthquake hit central Tottori prefecture on October 21, 2016. Our GNSS network, as well as GEONET revealed a detailed pattern of crustal deformation before, during, and after the earthquake. We report the deformation observed by GNSS and InSAR.

Deformation in the San'in shear zone is characterized by right-lateral shear movements. The 20-km-wide shear zone extends in an east-west direction and accommodates 5 mm/yr of shear movements. The M6.6 earthquake occurred in the shear zone.

Coseismic displacement was observed at our GNSS stations. The largest horizontal displacement is 9 cm toward east-southeast and the largest vertical one is subsidence of 4 cm. We estimate parameters of a rectangular fault model using the observed displacement. The estimated parameters suggest a vertical fault oriented NWN-SES with left-lateral strike slip, which is concordant with aftershock distribution. The estimated moment magnitude is ~6.2. SAR interferograms of ALOS-2 show a clear quadratic pattern of surface coseismic displacement.

Postseismic displacement at GNSS stations reached 2 cm as of end of December, 2016. Although a spatial pattern of postseismic displacement is similar to that of the coseismic displacement, observed postseismic displacement is concentrated near the source fault. It suggests shallow afterslip along the coseismic fault.

*J03-1-02
Joint Symposium / J03. Deformation of the lithosphere: Integrating seismology and ge odesy through modelling

Postseismic deformation following the 1995 Kobe earthquake detected by space geodesy

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A Mw 6.8 earthquake hit the city of Kobe, southwest Japan, and its surrounding area on January 17, 1995. The source faults, trending in the NE-SW direction, are estimated beneath the foothill of the Rokko Mountains, but it has a dominant right lateral strike slip components. The Rokko Mountains may have been built by the motion of active faults, but coseismic uplift may not be enough. There fore postseismic deformation might contribute to the building of the Rokko Mountains.

In order to study the postseismic deformation, we collected all available space geodetic data during about 20 years, including ERS-1/2, Envisat, JERS-1, ALOS/PALSAR and ALOS-2/PALSAR-2 images and continuous GPS data, and reanalyzed. Especially, temporal continuous GPS observation made by the Geographical Survey Institute, Japan in and around the Kobe area is important. We recalculated coordinates of these continuous GPS stations with recent PPP procedure using reanalyzed orbits and clocks of satellites.

Time series analysis of JERS-1 images revealed line-of-sight (LOS) decrease of the Rokko Mountains. PSInSAR results of ALOS/PALSAR also revealed slight uplift north of the Rokko Mountains. These observations suggest that the Rokko Mountains might have uplifted during the postseismic period.

LOS increase in a wedge shaped region between two active faults in the vicinity of the NE terminus of the source fault of the Kobe earthquake, which indicates that the subsidence between these two faults continued up to 2010. Continuous GPS observation during the first two years of the postseismic period shows north-south extension with right lateral motion between these two faults.

These observations suggest that the Rokko Mountains may have uplift till 2010. On the other hand, active faults near the NE terminus continued to slip with the formation of graben-like structure, due to coseismically loaded stress.

Slow Slip Events in Cascadia: Observation and Hazard Analysis Derived from Sentinel-1 InSAR

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Slow slip events (SSEs), also known as silent earthquakes or episodic tremor and slip (ETS), are earthquakes unfolding in slow motion. Energy release over a long time causes seismic waves with such long periods that the motion is imperceptible to all but the most sensitive instruments, and with little short-period shaking. The total moment released in an SSE may be quite large, and stress transfer from the event may either increase or relax elastically stored strain. It is important to understand the nature and impact of these often regularly-repeating and predictable events, and whether they are adding to hazard potential or ameliorating it.

Here we report on our efforts to help assess the earthquake hazard along the Cascadia region of the Pacific northwest and determine, from spaceborne InSAR data, if SSE events are affecting the earthquake risk. We produce spatially dense crustal deformation observations that, when used with the existing GPS and seismic data, can localize and assess the size of slow displacements. Our goal is to measure SSE crustal displacements in Cascadia, using InSAR with finer and more comprehensive coverage than the existing GPS network, to solve for both a model of the slip at depth and the potential for a large and destructive earthquake.

The challenge of InSAR over Cascadia is that the dense forest cover leads to significant InSAR decorrelation. We use persistent scatterer (PS) point identification, interpolation of the sparse phase field, inverse solutions optimized for transient detection, and separation of the secular and transient signals, which may allow for a superior assessment of the hazard potential of a massive earthquake in the Pacific northwest. This work is, to our knowledge, the first implementation of the type of hazard analysis from crustal deformation that has been shown in Hawaii and Mexico to an environment where nearly all of the surface is hidden beneath a very thick vegetation canopy.

*J03-1-04
Joint Symposium / J03. Deformation of the lithosphere: Integrating seismology and ge
odesy through modelling

Hidden Earthquake Potential in Plate Boundary Transition Zones

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Plate boundaries can exhibit abrupt changes in their tectonic deformation at triple junctions and other plate boundary transitions. At such locations, the superposition of two crustal deformational regimes may combine to generate displacement signals that do not reflect the actual earthquake cycle strain accumulation in the region. Two examples of this effect are in the vicinity of the Mendocino triple junction (MTJ) along the west coast of North America, and at the southern end of the Hikurangi subduction zone, New Zealand. In the region immediately north of the MTJ, the observed signal (GPS) of crustal displacements is intermediate between Pacific and Juan de Fuca (JdF) motions. With distance north, the signal rotates to become more aligned with JdF - NAm displacements - the motions expected along a coupled subduction interface. The deviation of that subduction interface signal near the MTJ has been previously interpreted to reflect clock-wise rotation of a coastal, crustal block and/or reduced coupling at the southern Cascadia margin. The geologic record is consistent with the signal reflecting the combined effects of northward crustal shortening (on geologic time scales) associated with the MTJ Crustal Conveyor overprinted onto the subduction earthquake cycle signal. At the Hikurangi to Alpine Fault transition in New Zealand plate interactions switch from subduction to oblique translation along the Alpine fault system. Here the signal recorded by GPS shows a reduction in plate motion-directed displacements, which has been interpreted to reflect reduced coupling. This signal records both the subduction interface coupling related to the megathrust earthquake cycle, and the shear deformation produced by the extensive right-lateral shear of the Marlborough Fault system. The relevance of this effect is seen in the recent (November 2016) Kaikoura earthquake, which ruptured the megathrust interface and produced strike slip displacements on upper-plate crustal faults.

*J03-1-05
Joint Symposium / J03. Deformation of the lithosphere: Integrating seismology and ge odesy through modelling

Interseismic Strain Partitioning in Nankai Subduction Zone, Southwest Japan: Block Movement and Internal Deformation of the Forearc Sliver

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We study interseismic strain partitioning in the Nankai subduction zone, southwest Japan (SWJ). Oblique subduction of the Philippine Sea plate (PHS) and strong coupling on the plate interface have deformed the overriding SWJ arc in two ways: interseismic crustal shortening in the direction of PHS convergence and long-term lateral block movement of the forearc sliver along the Median Tectonic Line (MTL) that is the arc-parallel strike-slip fault dividing the forearc from the rest of SWJ. Slip deficit on the MTL fault plane may disturb local deformation filed.

Basic data used in this study are GPS displacement rates obtained from the nationwide continuous network. We incorporate the rates from dense campaign measurements along two traverse lines across the MTL to improve spatial resolution around it. Furthermore we add seafloor displacement rates near the Nankai Trough to better estimate plate coupling far offshore. PHS interface and MTL fault plane are reproduced by many triangular elements to a depth of 50 km and 15 km, respectively. We introduce Markov Chain Monte Carlo method to simultaneously estimate slip deficit distribution on the PHS interface and MTL fault plane, together with the Euler vector of the forearc block motion relative to SWJ.

The slip deficit rate on the PHS interface is the strongest (> 50 mm/yr) at the depth of 15-25 km, which nearly overlaps with the main rupture zone at the last megathrust event in 1946. While the slip deficit rates decrease steeply toward the deeper portion, they are still large enough in a shallower zone near the trough. Rate of the forearc block motion is 5-7 mm/yr relative to SWJ but locking of the MTL fault plane is not uniform from east to west. The block motion across the MTL and partial locking of its boundary fault plane have caused a small-scale shear deformation zone in the SWJ arc.

*J03-2-01
Joint Symposium / J03. Deformation of the lithosphere: Integrating seismology and ge
odesy through modelling

Postseismic Deformation Following the 2002 Mw7.9 Denali Fault Earthquake

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An Mw7.9 strike slip earthquake struck on November 3, 2002, in central Alaska, rupturing ~325 km of the Denali fault and two other faults. The earthquake caused a strong postseismic transient that continues to have a substantial effect today. Distinguishing between different mechanisms of postseismic deformation (e.g., afterslip, viscoelastic relaxation) remains a challenging problem for many earthquakes. Early studies done in the first few years after the Denali event demonstrated that the observed postseismic response could not be explained by a single mechanism, but estimates of the contributions of afterslip and viscoelastic relaxation were plagued by tradeoffs between unknown parameters. As a result, the postseismic models determined using the first few years of data did not predict the future observations well.

We use a homogeneously reprocessed time series of GPS data from before and after the earthquake to reassess the postseismic deformation using as much as 15 years of data after the event. We analyze the variations in the time series themselves to identify subsets of the data in space and time for which a single postseismic mechanism is dominant. We also assess tradeoffs between the imprecisely known “steady" deformation and the postseismic transient. We compute the postseismic deformation using finite element models including realistic 3D elastic and viscoelastic structures, and constrain models based on the observations. One complexity is that the afterslip distribution, in practice, generally needs to be estimated empirically, although we experiment with models that base the afterslip distribution on the coseismic stress changes (which are uncertain due to incomplete knowledge of the coseismic slip). Coseismic and postseismic models are self-consistent, using the same earth structure, which eliminates an inconsistency in the previous studies.

Estimation of spatiotemporal distribution of interplate slip after the 2003 Tokachi-oki earthquake incorporating viscoelastic relaxation

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The 2003 Mw 8.0 Tokachi-oki earthquake is an interplate earthquake along the Kurile trench. Its postseismic deformation has been observed by GNSS [e.g., Miyazaki et al. 2004]. Estimation of spatiotemporal afterslip is a key to clarify the healing process after large earthquake. Because the postseismic deformation should be caused by both viscoelastic relaxation and afterslip, it is important to incorporate both effects for the modeling. In this study, we estimated a spatiotemporal interplate slip for about 7.5 years following the 2003 event as well as the coseismic slip of the 2003 and M 6-7 class earthquakes simultaneously. We included a viscoelastic response of interplate slip in the estimation of the slip.
For the data analysis, we corrected the effect of the 1993 Hokkaido-Nansei- oki earthquake for the observed GNSS data in Hokkaido by using the model of Ueda et al. [2003]. The secular velocity before the 2003 event was estimated from the corrected data and removed from the postseismic data. And then, we removed a seasonal variation and displacements of the M6-7 events in the postseismic period. Finally, we down-sampled the residual time series with an interval of 1-6 months. We used about 7.5 years long GNSS data until the 2011 Tohoku-oki earthquake.
For the modeling of postseismic deformation, we constructed a model consisting of the coseismic slip of the 2003 and the following M6-7 class events, interplate slip including afterslip following these events and viscoelastic relaxation. We assumed the two-layers viscoelastic structure estimated by Itoh and Nishimura [2016] to estimate interplate slip distribution.
A preliminary result shows large postseismic slip occurred in the up-dip and down-dip extensions of the coseismic slip region and implies an interplate coupling had not been recovered to that before the 2003 event at the time of the 2011 event.

*J03-2-03
Joint Symposium / J03. Deformation of the lithosphere: Integrating seismology and ge
odesy through modelling

Reconciling short and long term observations of megathrust cycles at subduction zones

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Regional models of the earthquake cycle have become increasingly sophisticated tools to understand the seismological and geodetic observations. They capture critical physical processes like (partial) locking of the plate interface, the detailed co-seismic slip, poro-elastic and mantle relaxation and afterslip. Emerging from both the observations and the models is that similar physical processes are active at different margins, and that part of the observed complexity is controlled by them being in different stages of the earthquake cycle. We use geodynamic models to isolate the geodetic and geological signature of these physical processes over many mega-thrust cycles. Co-seismic and subsequent slip on the subduction interface are dynamically (and consistently) driven. Our setup allows us to incorporate earthquake history, to access the sensitivity of the (short-term) seismological and geodetic signals to mechanical properties of the overriding plate/slab system, and to predict (longer-term) geological imprints. We find that the mega-thrusts induce significant tensile stresses in the overriding plate near the down-dip end of the co-seismic fault. Down-dip afterslip reduces these tensile stresses, and observed aftershocks agree with fast slip during a short period here. Transient tectonic uplift and subsidence of the overriding plate results from flexure/buckling. Permanent deformation of the overriding plate accumulates slowly inboard of the locked plate contact in response to long-term compression. We discuss the potential of thrust faults in the overriding plate for producing transient uplift/terraces. We review pre-, co- and post-seismic observations and conclude that our models capture the principal aspects of megathrust cycles that are shared by many margins, including that in Chile, in Alaska-Aleutians, Sumatra-Andaman, and in the Japan Trench margin.

*J03-2-04
Joint Symposium / J03. Deformation of the lithosphere: Integrating seismology and ge
odesy through modelling

Heterogeneous interseismic coupling along the Peruvian subduction zone and rigid motion of the Peruvian Sliver

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Over 100 survey and continuous GPS measurements acquired in Peru between 2008 and 2013 provide new insights into the present-day crustal deformation of the Peruvian margin. The GPS velocity field together with information of compiled active faults reveal the rigid motion of the Peruvian Forearc Sliver extending from the trench to the boundary between the Western and Eastern Cordilleras, moving southeastward at a rate of 4-5 mm/yr relative to the stable South America. GPS data also reveal that tectonics in the Cordillera Oriental is dominated by 2-4 mm/yr of crustal shortening accommodated along the sub-Andean fold and thrust belt. In a local Peruvian Sliver reference frame the residual GPS velocity field reflects important lateral variations of the GPS gradients which attest for along-strike heterogeneous pattern of interseismic coupling along the megathrust. Heterogeneous interseismic coupling models indicate shallow and relatively weak coupling in northern Peru, deep and highly locked asperities distributed along the central and southern Peru coasts. These coupling patterns are consistent with past moderate tsunami-earthquakes in northern Peru and with the rupture areas of large and great megathrust earthquakes in central and southern Peru suggesting that seismic asperities might be persistent features of the subduction megathrust. Creeping segments correlate with the location of rupture limits of great past earthquakes and with the location of ridges and fracture zones supporting their role as seismic barriers to rupture propagation. In Central of Peru, where the great 1746 Mw˜9.0 Lima-Callao occurred, the current interseismic moment deficit would suggest a recurrence time of at least 305 +- 40 yrs to reproduce a similar event. The occurrence of the 1940-2007 sequence of Mw˜8.0 earthquakes may increase this recurrence time only by 30%.

*J03-2-05
Joint Symposium / J03. Deformation of the lithosphere: Integrating seismology and ge
odesy through modelling

Crustal deformation and surface kinematics after the 2010 earthquakes in Latin America

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A continuous crustal deformation model for Latin America and the Caribbean inferred from GNSS measurements gained after the strong earthquakes occurred in 2010 in Chile and Mexico is presented. This model is based on a multi-year velocity solution for a network of 456 continuously operating GNSS stations covering a five years period. The deformation model is computed from the discrete station velocities using the least square collocation (LSC) approach with empirically determined covariance functions. While the effects of the Baja California earthquake can be considered as local, the effects of the Maule earthquake changed the surface kinematics of a large area (between the latitudes 30S-45S from the Pacific to the Atlantic coasts). Before the Maule earthquake, the strain rate field in this area showed a strong west-east compression with maximum rates of about 0.40 micro-strain/a. In accordance, the deformation vectors were roughly parallel to the plate subduction direction and their magnitudes decreased with the distance from the subduction front. After the earthquake, the largest compression (0.25 micro-strain/a) occurs between the latitudes 37S and 40S with a N30E direction. The maximum extensional strain rate (0.20 to 0.35 micro-strain/a) is observed in the Sub-Andean zone in the Patagonia south of latitude 40S. The extensional axes rotate from a N30E direction in the central Araucania zone to a westerly direction of N72W in the western part of Patagonia. In the northern region of parallel 35S, the extension is also directed to the Maule zone (S45W) but with quite small rates. This complex kinematics causes a large counter clockwise deformation pattern rotating around a point south of the epicentre (35.9S, 72.7W). The magnitude of the deformation vectors varies from 1 mm/a close to the rotation point up to 22 mm/a near the 2010 earthquake epicentre. The direction of the largest deformation vectors points to the epicentre.

*J03-3-01
Joint Symposium / J03. Deformation of the lithosphere: Integrating seismology and ge
odesy through modelling

Modeling lithospheric tectonics with space geodesy: the problem of timescales

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Space-based geodesy has provided unprecedented details of crustal kinematics that have been widely used in models of lithospheric dynamics, but the results are sometimes unsatisfactory and confusing. The problem arises from the timescale-dependent lithospheric rheology. Space-based geodetic measurements, usually over a few years, take snapshots of the deforming crust that is often dominated by transient elastic or viscoelastic strain. The tectonic evolution of lithosphere, however, only leaves permanent (plastic) strain in geological records. Thus using space-based geodetic measurements in long-term lithospheric dynamic models requires consideration of all elastic, viscous, and plastic strains. I will illustrate this challenge in our studies of tectonic evolution in western US, the Andes, and the Tibetan Plateau. In the southwestern US, crustal kinematics delineated by the GPS measurements differs significantly from that reconstructed from the geological records, leading to different estimates of the driving forces. Our numerical model shows that the GPS data is dominated by the transient viscoelastic shear strain across the Pacific-North American plate boundary zone. The geological strain in the past few million years, on the other hand, reflects mainly the extensional strain driven by gravitational collapse of the Basin and Range Province. Across the Andean orogenic belt, the GPS-measured crustal shortening is largely elastic and tends to be restored by repeated trench earthquakes, whereas permanent strain accumulates in the subandes where the plastic strength of the crust is lower than that of the plate interface. Across the Himalayan-Tibetan orogen, deformation by the indentation of the Indian plate is largely limited to the Tibetan Plateau, whereas gravitational potential energy is chiefly responsible for the widespread crustal deformation measured by GPS in much of central and eastern Asia.

*J03-3-02
Joint Symposium / J03. Deformation of the lithosphere: Integrating seismology and geodesy through modelling

Anisotropic horizontal thermal contraction of young oceanic lithosphere inferred from stress release by oceanic intraplate earthquakes

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1. Introduction
Oceanic lithosphere experiences thermal contraction, which is up to 3 % in volume, due to cooling after it is generated at oceanic ridges. Thermal stress due to thermal contraction is the main cause of oceanic intraplate earthquakes (OCEQs). One unresolved problem regarding this phenomenon is how freely the oceanic lithsphere contracts in horizontal directions due to thermal contraction. In other words, how is the boundary condition of the oceanic lithosphere? This is important for estimating driving/resistive forces of mantle convection through force equilibrium of lithosphere, and clarifying the cause of orthogonal ridge-transform fault systems. Thus, this study attempted to estimate the horizontal thermal contraction rates of the oceanic lithosphere by analyzing stress release due to observed OCEQs.

2. Method
First, we analyzing each component of stress release due to observed OCEQs in world oceanic lithosphere in 1964-2015. We found strong anisotropy of stress release in young oceanic lithosphere (5-15Ma) that extensional stress release dominates in the ridge-parallel component and compressional stress release dominates in the spreading-directional component. Next, we conducted a numerical simulation of thermal stress evolution of the oceanic lithosphere in order to investigate how large anisotropy of thermal contraction can explain the observed anisotropic stress release.

3. Results and Discussion
By comparing the observed and modeled brittle stress release rates, we found that ridge-parallel contraction rates of young oceanic lithosphere are only 0-30 % of spreading-directional contraction rates; it means strong anisotropic horizontal thermal contraction. This smallness of ridge-parallel contraction produces extensional thermal stress in the ridge-parallel component, which may play a role of weakening of long transform faults by reducing normal stress on the transform faults.

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GPS observation of Biot's slow wave in the Earth's crust triggered by Hurricane Sandy's storm surge

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A phenomenon predicted by *Biot (1956) is an ultra-slow (subsonic) wave in a poroelastic medium with high permeability, in which the fluid and surrounding matrix oscillate with opposite phase. Although there is evidence for Biot's slow wave in specially constructed laboratory settings, its direct observation in nature has remained elusive owing to rapid attenuation and a lack of natural low frequency (~0.1 mHz) excitation sources. Our routine determination of thousands of GPS positions around the globe with centimeter accuracy every 5 minutes presents the opportunity to search for poroelastic phenomena in the relevant bandwidth between seismic and tidal frequencies. Here we show, using 5-minute GPS data observed in northeast USA around the landfall of Hurricane Sandy of October 29-30, 2012, evidence of a highly-attenuated wave propagating in the Earth's crust over hundreds of km inland at ~65 m/s with ~12 cm amplitude. Such a phenomenon is consistent with Biot's slow wave being triggered by the associated 4-m storm surge, then propagating in a highly permeable crust with abundant fluid-saturated interconnected cracks. The ability to observe such waves opens a new window on Earth's poroelastic structure, with prospects to better understand connections between hydrology, seismology, geodesy and tectonics.

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*J03-3-04
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Performance of 3-D Surface Displacement Measurement from Sub-pixel Correlation of Optical Imagery and InSAR: a Multi-Sensor Approach

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The main objective of this research is to calculate the three-dimensional (3-D) surface displacement fields using optical image sub-pixel correlation and interferometric synthetic aperture radar (InSAR) technique to investigate the events: Gorkha (2015), Kashmir (2005), and Duzce (1999). To help reach the goal, imagery from multiple sensors e.g. ASTER, SPOT, Sentinel, ERS and ENVISAT were employed. Earthquake surface displacement in the satellite line of sight (LOS) direction is measured by InSAR analysis and the optical image sub-pixel correlation technique provided the horizontal surface displacement components. The vertical component of surface displacement was derived from these horizontal and LOS components. The performance of this 3-D surface displacement measurement approach was validated by field and GPS measurements.

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odesy through modelling

Lithosphere dynamics and earthquake simulation: implication for seismic hazard analysis

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Understanding of lithosphere dynamics, tectonic stress localization, earthquake occurrences, and seismic hazards has significantly advanced during the last decades. Modeling of lithosphere dynamics and earthquake simulations coupled with a seismic hazard analysis can provide a better assessment of potential ground shaking due to earthquakes. We employ a model of lithospheric block-and-fault dynamics constrained by geological, geophysical, and geodetic observations to simulate earthquakes in a seismic-prone region. This model allows for studying the influence of fault network properties and regional movements on seismic patterns. The model's performance is analyzed in terms of reproduction of basic features of the observed seismicity such as the frequency-magnitude relationship, clustering of earthquakes, fault slip rates, and earthquake mechanisms. We present results of our studies related to modeling of lithosphere dynamics in the Caucasian and Tibet-Himalayan regions. We use then the simulated large seismic events together with observations (recorded and historic earthquakes) for probabilistic seismic hazard assessment, and discuss how hazard assessment can be improved.

*J03-P-02
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odesy through modelling

Analysis of Detailed Crustal Strains due to the Dense GNSS Array in the Tokai Region, Central Japan

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The Tokai region is an area of scientific interest where the Philippine Sea plate subducts from the eastern end of the Suruga-Nankai Trough in the south of the Japanese Islands, and is expected to generate a large interplate earthquake in the near future. Recent investigations suggest that the largest possible earthquake in this region could be M9 class earthquake, and is called as the Nankai Trough earthquake. Moreover, the area has experienced long-term slow slip events (SSE) during 2000-2005 and since around 2013. The Japanese University Consortium for GNSS Research (JUNCO) established a dense GNSS array in the region and started observation in around 2004 for monitoring the crustal deformation. The array is an augmentation of the GEONET, the nationwide GNSS array established by the Geospatial Information Authority of Japan (GSI). The network consists of more than 50 GNSS sites and is denser with 5-10km baseline lengths, compared with the 20km spacing of GEONET.
The data taken by the network has been used to monitor the strain accumulation in the area as well as to investigate slip evolution of the long-term SSE. This study shows temporal change of strains for the observed 12 years up until 2016. Results show strong disturbances from nearby large earthquakes of the 2009 August Suruga Bay earthquake (Mw6.3), and the 2011 Off Tohoku earthquake (Mw9.1). In particular, the Suruga Bay earthquake affected the area with significantly complicated strain pattern, suggesting importance of dense GNSS array introduced in this study. We are now archiving the obtained data together with ancillary data for making the data available more publicly for further researches in the area.

*J03-P-03
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odesy through modelling

The topography of the lithosphere-asthenosphere boundary beneath the Korean Peninsula from S receiver functions

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The topography of the lithosphere-asthenosphere boundary (LAB) beneath the Korean Peninsula was determined using teleseismic S-receiver functions, obtained from the seismographs in Korea from 2005 to 2012. The receiver functions were migrated from the delayed time to the corresponding conversion points (CCP) of S-to-p phases using the IASP91 model and stacked with the common conversion points in circular bin. The LAB beneath the Korean Peninsula was determined at a depth range of 60 - 100 km from the CCP stacked receiver functions. The LAB depth is deep at the north and getting shallow to the south with a rapid change along the tectonic boundary between the Gyeonggi Massif and the Okcheon Fold Belt. This shallow LAB, considering the Precambrian bedrock of the Korean Peninsula, implies the lithosphere thinning accompanied by the coeval subduction of the paleo-Pacific plate since the Jurassic. The northward subduction of the oceanic plate from the southeast in the Jurassic could result in the northward dipping of the LAB depth beneath the Korean Peninsula. The structure in the uppermost mantle reflects the complex tectonic history surrounding the Korean Peninsula. Therefore, the LAB topography reveled in this study would contribute to understand the tectonic history of the Korean Peninsula.

*J04-1-01
Joint Symposium / J04. Geohazard early warning systems

ShakeAlert@taiwan

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The Earthquake Early Warning System (EEWS) based on the low-cost P-Alert seismic network in Taiwan has proved indispensable by a few earthquake events since 2010. This dense network can produce detailed shaking maps and identify direction of source rupture in almost real-time. Equip with real-time acceleration data and the time-dependent attenuation relationship of peak ground acceleration (PGA), our system, ShakeAlert@taiwan, can compute predicted PGA immediately before the observed PGA arrive. This advantage can provide sufficient time for hazard assessment and emergency response, comparing to the conventional shaking map. The performance of ShakeAlert@taiwan was tested against historical moderate-to-large inland earthquake (ML > 5.5) events. Take 2016/02/5 Meinong, Taiwan earthquake as an example, it converge to stable result and produce shaking map within 16 seconds after the earthquake occurred. The processing time for possible maximum PGA, taking into account the PGA saturation, can be reduced to 8 seconds. In comparison with traditional methods, ShakeAlert@taiwan can quickly identify possible damage region and provide the valuable warning information for hazard mitigation.

*J04-1-02
Joint Symposium / J04. Geohazard early warning systems

Challenges for implementing Earthquake Early Warning: A Case Study in Nicaragua

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Earthquake early warning (EEW) systems aim at providing fast and accurate estimates of event parameters or local ground shaking over wide ranges of source dimensions and epicentral distances. Numerous approaches, in a variety of tectonic settings, are already operational and warnings publicly available in some regions.
The Swiss Seismological Service (SED) has integrated EEW solutions into the SeisComP3 (SC3) professional earthquake monitoring software. VS(SC3) provides fast magnitude estimates for network-based point-source origins using conventional triggering and phases association techniques, while FinDer(SC3) matches the evolving patterns of ground motion to track on-going rupture extent, and hence can provide accurate ground motion predictions for finite fault ruptures. SC3 is widely used, including in Central America, and at INETER in Nicaragua.
SED and INETER started a joint project to assess the feasibility of EEW in Nicaragua and Central America and to set up a prototype EEW system. We test VS(SC3) and FinDer(SC3) softwares at INETER since 2016. We report on the successes and challenges of operating an EEW system where seismicity is high, but infrastructure is fragile and the design and operation of a seismic network is challenging (in Nicaragua, on average 50% of all stations do not work effectively for EEW). Broad seismic data exchanges in Central America provides real time data at INETER from stations operated by neighboured countries. We compare the observed performance of EEW in Nicaragua with an ideal setting, featuring optimized network geometry and latency. Without a reliable network, it is impossible to guarantee EEW with a minimum number of missed and false alarms. Implementation of EEW under these conditions can lead to loss of confidence in the system by end-users. We make proposals to improve the Nicaraguan and the Joint Central American Seismic Networks for EEW.

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*J04-1-03
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Reducing Digitiser Latency for Earthquake Early Warning: New Strategies for Seismic Hardware

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The latency between earthquake origin and issuing an alert is one metric used to assess the performance of Earthquake Early Warning Systems. Total latency accumulates from many sources (e.g. P-wave propagation, digitization, transmission, receiver processing, triggering, event declaration). Data delivery latency is the time taken for digitization, packetisation, transmission and receipt of data. The two main contributors to data delivery delays are data packetization (Brown et al., 2011) and digitisation.

Data packetisation: SEEDlink protocol is commonly used, however, packet size is fixed to 512-byte miniSEED records; each with a 64-byte header. SEEDlink can cause typical large data transmission latencies of >0.7 s at typical sampling rates. We propose a new ultra-low-latency protocol, GDI, an efficient and flexible method of exchanging data between seismic stations and data centers in large networks. Instead of fixed-length packets, GDI dispatches data sample-by-sample as acquired by the data-logger. A self-adaptive scheme assesses available bandwidth and judges the smallest packet size needed for the fastest transmission. A light 4-byte header maximizes efficiency for small packet sizes.

Digitisation: Most current seismic data-loggers implement acausal (linear phase FIR) filters; but these cannot be computed in true real-time and give spurious precursors to seismic wave onsets (e.g. Scherbaum & Bouin, 1997). Acausal filtering typically contributes >0.3 s to data delivery delays. Causal (minimum phase) FIR filters are typically non-standard in seismic data-loggers, yet, the improved latency and sharper onset determination mean that causal filters offer significant advantages for EEWS, reducing digitization delays to 20–60 ms (at sample rates of 100–250 sps).

Using a twofold strategy of causal filtering combined with a rapid data transmission protocol, such as GDI, we show significantly reduced data delivery latencies to 40–60 ms (at typical sample rates).

*J04-1-04
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A new methodology for Earthquake Early Warning (EEW) by a high-dense seismic network deployed at interstation distance of less than 5 km

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Many of current EEW systems issue estimated intensity distribution maps according to empirical attenuation relationships which require information of source parameters and focal distance. These information are determined based on point source model which is not applicable for finite source model of large earthquakes. EEW is essential for the source area of inland earthquakes where heavy damages are expected. In most cases, EEW is issued lately in the source area which described as “a blind zone". Seismic networks, in case of Japan, are deployed for the determination of hypocenter at about 20-30 km interstation distance. That span delays the detection of P-wave arrivals by about 3-4 s. In this study, we present a new methodology for EEW which used peak ground acceleration (PGA) estimated from P wave, taking advantage of the differential velocity (i,e., ~1.73) and the amplitude ratio (i,e., ~1/5) of P and S-waves. The efficiency of this method suggests the distribution of a high-dense seismic network of 5 km interstation distance, considering a span distance less than that of velocity of P-wave (i,e., 6 km/s). The slowness analysis of P waves tells information of the rupture starting point and its depth. Firstly, peak ground acceleration (PGA) on free surface is estimated from maximum P-wave amplitude in one-second time step until the arrival of S-wave at the first detected station, and then adjusted to that on the engineering base (PGAE) by eliminating the site effect. Secondly, we estimate PGAE on far site from a relevant attenuation relationship and adjusted to PGA considering site amplification. Finally, we issue real-time intensity map in every second time step till the declining of PGA. The described method is useful to improve EEW system and also to perform disaster estimation immediately after the occurrence of large event, in order to avoid data extrapolation and the time consuming waveform inversion analysis.

Magnitude scaling relationships from the first 3s of P-wave arrivals in Mainland of China

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One of the critical technologies of earthquake early warning is determining the size of an earthquake from the first few seconds after the P-wave arrivals. We derive empirical magnitude scaling relationships for mainland of China using a dataset of 214 past earthquakes and 2511 vertical waveforms recorded in mainland of China by China Strong Motion Networks Center (CSMNC) between 2007 and 2015. The events range in magnitude from 4.0 to 8.0. We use the predominant period (tau-c) and the peak displacement amplitude (Pd) measured from the first 3 seconds of P-wave arrivals to determine period-magnitude and amplitude-magnitude scaling relationships respectively. The average error in magnitude estimates is 0.3 magnitude units for events with magnitudes ranging from 4.0 to 6.5, and 0.5 magnitude units for events with magnitudes greater than 6.5. we observe the saturation effect for magnitudes greater than 6.5, especially in amplitude-magnitude scaling relationships. In cases of the Ms 8.0 Wenchuan earthquake and the Ms 7.0 Lushan earthquake, such warnings would be available within 10s of the origin time of a large earthquake. Our magnitude scaling relationships may be useful for developing an earthquake early warning system in mainland of China.

*J04-2-02
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A Fast Algorithm for Earthquake Early Warning Systems Based on the Energy release of P Waves in the Interval tS-tP

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The Mexican earthquake alert system (SASMEX), operating since 1991, is in a unique situation because seismic waves that potentially damage Mexico City take approximately one minute to reach the soft soils of the city. Today, the system covers the entire Mexican subduction zone. As a result, cities close to the seismic zones were added to the system and alerted also of impending earthquakes. In those cases, the processing time of the original algorithm is relatively long, as it is based on the energy released in twice the S-P interval. We present another algorithm, which measures the maximum seismic energy released and the cumulative energy growth in the S-P period. The algorithm detects the P wave and measures the energy growth, which is in turn calibrated to magnitude and decides whether a magnitude threshold is exceeded. The algorithm stops when the S wave arrival is detected. Seismic field sensors need to be near the epicenter and at least two nearby instruments should confirm the potential alert. A regression model based on records from 144 subduction earthquakes 4.7>Mw<8.1 calibrated the magnitude estimator M(tS-tP). The magnitude is determined with a family of linear equations, which relate it to the sum of squared accelerations and the maximum acceleration. The algorithm was tested on a subset of 97 earthquakes. The threshold to activate the early warning system is magnitude M(tS-tP) >5.8. Out of 97 events, 93 were correctly classified with a magnitude larger than 5.8, demonstrating the robustness of the method. The south Napa earthquake (Mw6) is an excellent example where strong motion data was recorded nearby. The application of the tS-tP algorithm to the 24 August 2014, Napa earthquake shows that in this hypothetical scenario, the tS-tP algorithm would give a warning time of 10 seconds to the city of Berkeley. In comparison, the ShakeAlert algorithm provided a warning time of only 5 s.

*J04-2-03
Joint Symposium / J04. Geohazard early warning systems

Seismogeodesy for Rapid Earthquake Magnitude Estimation

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Earthquake magnitude is a concise metric that provides invaluable information about the destructive potential of a seismic event. Rapid magnitude estimation for earthquake and tsunami early warning relies on near-field seismic and geodetic instruments. However, seismic instruments experience well-documented complications at long periods, which hinders accurate and timely estimates of ground displacement. As such, the relation between ground motions measured with strong-motion accelerometers (broadband seismometers clip in the near field of large earthquakes) and magnitude saturates, leading to underestimation of earthquake magnitude. However, ground motions measured with GNSS do scale with magnitude without saturation [Crowell et al., 2013; Melgar et al., 2015]. Therefore, we supplement high frequency strong-motion accelerations with Global Navigation Satellite System (GNSS) long-period displacement observations to better inform rapid response. We refine magnitude scaling relations using peak ground displacement (PGD) by adding a large GNSS dataset of earthquakes in Japan. We demonstrate that seismogeodesy, the optimal combination of GNSS and seismic instrumentation, improves the sensitivity of displacement time series compared to GNSS alone. This not only means that ground motion can be detected at farther stations, but also that smaller seismic arrivals (i.e. P-waves) become visible in the displacement time series. P-wave amplitude (Pd) has been examined as an early indicator of earthquake magnitude. Relations between Pd and magnitude using seismic-only instruments also appear to suffer from saturation, while seismogeodetic data has been demonstrated to eliminate saturation [Meier et al., 2016, Crowell et al., 2013]. We create seismogeodetic displacements by combining the GNSS dataset with Japanese KiK-net and K-net accelerometer data to explore the potential of seismogeodesy for magnitude scaling using P-wave amplitude with several seconds of data.

*J04-2-04
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Determination of warning earthquake magnitude from the initial P-wave recordings based on half periods and characteristic periods

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The determination of earthquake magnitude from the first several seconds of P-waves is fundamental in earthquake early warning (EEW) systems. There exist kinds of method to estimate the magnitude of ongoing earthquake, including peak displacements, characteristic periods and predominant periods. In this paper, the half period of the P-wave is implemented to determine the warning earthquake magnitude. Different seismic events in different regions of strong motion records is used to study the differences in the half periods of the first P waves. This paper discusses the characteristics at the beginning of waveforms in the Wenchuan mainshock and aftershock events and determines the correlation between the motion of moderately strong earthquakes in the early half cycle parameters and the earthquake magnitude. The effect of attenuation relations studied in the P wave seismic phase to S-wave phase time range, peak displacement with the time window length increases the variation characteristics, and different magnitude between peak displacement curve regularity is also investigated. Characteristics of cycle parameters in the P-waves for the records in the same time azimuth angle with the variation of the time window is also studies similarly. According to the research results, it is shown that there is a difference in the initial rupture of the earthquake with different sizes. In addition, this paper also discusses the relationship between the initial moving half period, the characteristic period and the source scale.

*J04-3-01
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Testing of GMPEs for absolute velocity response spectra for earthquake early warning of long-period ground motion intensity in Japan

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We constructed ground motion prediction equations (GMPEs) for absolute velocity response spectra (AVRS) at periods between 1 s and 10 s with an objective of rapid prediction of long-period ground motion intensities recently proposed by Japan Meteorological Agency (JMA) for earthquake early warning (EEW) (Dhakal et al. 2015). The GMPEs require JMA magnitude and hypocentral distance as basic input parameters and the values are corrected for site conditions a priory defined. The JMA magnitude, that is an amplitude-based magnitude, is estimated faster than moment magnitude. The success of predictions for future events depends on whether the future events are sufficiently similar to the trained events in the GMPE models in terms of location, magnitude, and individuality of the events. The GMPEs used data from events having Mw >= 6.5 and recorded by K-NET and KiK-net until 2012. In this paper, we discuss performance of the GMPEs for recent large earthquakes that occurred in Japan after the construction of the GMPEs. We found that the GMPEs performed satisfactorily in the region of high intensities but performed relatively poorly at distances beyond about 200 km in the case of the 2016, Mw 7.1 Kumamoto earthquake. We found that the event errors associated with the Kumamoto earthquake are quite larger than those for the events employed in the GMPEs. It is found that a part of the errors is from a bias due to an uneven azimuthal coverage of the data at long distances. For other large events that occurred in off the Pacific Coast of Japan (e.g., 2016 Nov 22, 05:59 JST, Mw 7.0, east off Fukushima Prefecture earthquake; 2015 Feb 17, 08:06 JST, Mw 6.7, far east off Sanriku earthquake), we found that the results are satisfactory.
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*J04-3-02
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Real-time prediction of ground shaking without source information: Data assimilation and simulation of seismic wave propagation for Earthquake Early Warning

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Many of the present Earthquake Early Warning (EEW) systems quickly determine the hypocenter and magnitude, and then predict strength of ground motions. The Mw 9.0 Tohoku earthquake, however, revealed some technical issues with such methods: under-prediction at large distances due to the large extent of the fault rupture, and over-prediction because the system was confused by multiple aftershocks that occurred simultaneously. To address these issues, we have proposed a new concept for EEW (Hoshiba and Aoki, 2015, BSSA), in which the present wavefield is estimated precisely in real time by applying data assimilation, and then the future wavefield is predicted by simulation of seismic wave propagation. Information on the hypocenter and magnitude is not required. We call it “numerical shake prediction" by analogy to “numerical weather prediction" in meteorology.
In many methods of the present EEW systems, the strength of ground motions (PGA, PGV, seismic intensity) are predicted using the hypocentral distance and magnitude based on a ground motion prediction equation, which usually leads the prediction of concentric distribution. However, actual ground shaking is not always concentric, even when site amplification is corrected. The strength of shaking may be much different among earthquakes even when their hypocentral distances and magnitudes are almost the same. For some cases, PGA differs more than 10 times, which leads to imprecise prediction in EEW.
In numerical shake prediction, because future is predicted from the present condition, it is possible to address the issue of the non-concentric distribution. Once the heterogeneous distribution is actually observed in ongoing wavefield, future distribution is predicted accordingly to be non-concentric. We will indicate examples of M 6 crustal earthquakes occurred at central Japan, and the 2016 Kumamoto earthquake (Mw 7.0), during which M 6 class earthquake was remotely triggered apart from 70 km from the epicenter.

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Real-Time Ground Motion Prediction based on Radiative Energy Transfer using Front-Site Waveform Information and Data Assimilation for the Application to Regional Earthquake Early Warning

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In-time warning of strong ground motion for citizens in affected areas is one of the primary objectives of Earthquake Early Warning. To satisfy this requirement, continuous front-site observation and quick analyzing algorithm to ensure enough warning time are indispensable. Existing network systems depend on fast source parameter estimation while on-site methods try to predict ground motion from an observation at a target site. Latter systems are currently the fastest approach for highly vulnerable sites, but they lack on quality in prediction. This study uses the radiative transfer theory based on ray scattering, to model a real-time numerical ground motion map for the region of Miyagi. The authors use a two-layered model to represent processes in geological structures by simulating the energy transfer in the bedrock as a function of scattering. The processes on the surface layer are then modeled as a function of local amplification and the bedrock information. Prediction is done for a circular area with an observation site as the central point. The predictive model uses band-passed filtered acceleration information from surface stations, projected onto the bedrock layer, by using a scalar transfer function. An energy impulse, which is a function of the PGA for a time length dt is then used to simulate the distribution of energy within the area. Surface intensity is estimated by multiplying the bedrock model with the surface amplification. This process is repeated in steps of dt second and can be done almost instantaneously. Furthermore, by using other observation sites within the prediction radius, evaluation and correction of the predictive field are achieved using data assimilation. The developed system allows it to model an interpolated wave-field behind, and a predicted wave-field in front of the wave-front, thus providing ground motion information around recording sites. The authors currently work on the extension of the proposed method into a network.

*J04-3-04
Joint Symposium / J04. Geohazard early warning systems

Propagation of local undamped motion (PLUM) method and its improvement using P-phase discrimination for more rapid earthquake early warning based on wavefield-estimation approaches

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Earthquake early warning methodologies based on wavefield estimation have been recently proposed by Hoshiba (2013) and Hosiba and Aoki (2015) to address technical challenges that come from point-source-model approaches such as underprediction of strong motion when large earthquakes (M>˜8) occur and overprediction when multiple earthquakes simultaneously happen. The propagation of local undamped motion (PLUM) method is a simple wavefield-estimation algorithm derived from the method proposed by Hoshiba (2013). The PLUM method predicts strong motion at a target site by taking the maximum among real-time seismic intensities (Kunugi et al., 2013) observed at seismometers within 30km of the target site. A simulation of the PLUM method for the 2011 off the Pacific coast of Tohoku Earthquake (Mw 9.0) (the Tohoku-oki earthquake) showed that the PLUM method predicted accurate seismic intensities in the Kanto region, where the EEW system of the Japan Meteorological Agency (JMA) underpredicted strong motion.

The PLUM method, however, has room for improvement in rapid warning issuance since its prediction process rely only on strong motion by S phase and do not utilize P-phase information available before the S-phase arrival. We introduced a simple P-phase discriminator that uses V/H (ratio of vertical to horizontal components of acceleration) and modified the prediction process of the PLUM method. The modified method first conducts on-site prediction of S-phase strong motion for seismometers assumed to be observing P phase. After that, the modified method predicts strong motion for target sites in the same way as the original method. We applied the modified method to the Tohoku-oki earthquake and the Mj 6.5 and Mj 7.3 earthquakes in the 2016 Kumamoto earthquake sequence. Results showed that the modified method provided longer warning times by 5 s in the Tohoku-oki earthquake and 1 s in the Mj 6.5 and Mj 7.3 earthquakes, compared with the original method.

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Recent advances in tsunami warning and earthquake early warning of the Japan Meteorological Agency after the 2011 Great Tohoku Earthquake and Tsunami

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The Japan Meteorological Agency (JMA) is the sole organization to issue warnings on natural hazards in Japan. JMA started its operation of tsunami warnings in 1949 and since then JMA has improved its warnings in accuracy and swiftness. And JMA started the service of earthquake early warning (EEW) provision to the public in 2007. For the 2011 Great Tohoku Earthquake and Tsunami (Mw9.0), JMA issued Major Tsunami Warnings, the highest category of JMA's tsunami warning, in three minutes, and issued EEWs 8.6 seconds after the earthquake detection. These warnings were promptly disseminated to the public via various ways such as TV, radio and mobile phones. On the other hand, this event also posed several issues to be improved on JMA's warning systems, and JMA took various measures based on the lessons learned from this event. Major countermeasures for tsunami warnings are, 1) introduction of qualitative expression of tsunami height estimation like "Huge", which will be used when JMA issues tsunami warnings based on pre-assumed maximum magnitude because the earthquake is too large to estimate the magnitude appropriately within around three minutes, and 2) utilization of ocean bottom pressure gauges in updating tsunami warnings. Regarding EEW, as the countermeasure for the difficulty in hypocenter and magnitude estimation when multiple events occur simultaneously, JMA introduced the Integrated Particle Filter (IPF) method in 2016, which is expected to greatly improve the ability to separate individual events from simultaneously occurred multiple earthquakes. JMA also plans to introduce the new method, i.e., the propagation of local undamped motion (PLUM) method, into EEW in the near future which addresses the issue of under-prediction for massive earthquakes with large rupture zones. This method adopts the technique of sequential prediction of seismic intensity by assimilating expanding ground tremor observations into forecasting.

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Geo-hazard early warning systems: A UNESCO perspective

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The Sendai Framework recognises the need to "substantially increase the availability of, and access, to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030". UNESCO strongly believes in the benefits of individual, cluster and multi-hazard early warning systems to better address the specificities of each hazard in an integrated manner. While considerable progress has been made in the field of early warning, these systems continue to be less developed for geo-hazards and significant challenges remain in advancing their development for specific hazards, particularly for sudden-onset hazards such as earthquakes. Furthermore, there is a need for better collaboration among and across communities of scientists, practitioners and policy-makers worldwide. As the only UN agency with a mandate in Earth Sciences, UNESCO is actively engaged in promoting cooperation, knowledge exchange and capacity building on geo-hazard early warning across the globe. By operating at the interface between science, education, culture and communication, UNESCO is best placed to facilitate the establishment of these systems. UNESCO recently launched the International Platform on Earthquake Early Warning Systems, to assess the state of the art in earthquake early warning globally and foster dialogue for capacity building and policy making around these systems. In line with this mandate, UNESCO is organising an International Conference on Earthquake Early Warning Systems in October 2017. UNESCO also promotes landslide early warning through the International Consortium on Landslides and has produced a study on mobile early warning systems for volcanic eruptions. Finally, UNESCO leads the Intergovernmental Oceanographic Commission, which coordinates the establishment of tsunami early warning systems worldwide. Thanks to its key role in promoting early warning systems, UNESCO is part of the International Network on Multi-Hazard Early Warning Systems.

*J04-4-02
Joint Symposium / J04. Geohazard early warning systems

Real-Time Tsunami Inundation Forecast System using NIED S-net

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One of the lessons learned from the 2011 Tohoku earthquake is the importance of offshore observations. JMA issued the initial tsunami warning three minutes after the 2011 Tohoku earthquake, however, estimated tsunami heights were underestimated. Although the estimated tsunami heights were raised about half an hours after the earthquake occurrences, the power failures prevented the residence from receiving updated tsunami information. It consequently caused enormous fatalities and significant damages to the eastern Pacific coast of Japan, indicating the importance to deliver prompt and accurate forecast of earthquake and tsunami to the onshore residences. The Japanese government decided to construct the Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net), which is operated by National Research Institute for Earth Science and Disaster Resilience (NIED). NIED S-net is expected to provide additional lead time for earthquake and tsunami early warning. We develop a new realtime tsunami inundation forecast system using NIED S-net. In our system, several appropriate tsunami scenarios that can explain offshore tsunami observations are quickly selected by using multiple indices from the Tsunami Scenario Bank (TSB), which contains offshore tsunami pre-calculated waveforms, coastal tsunami heights, inundation depth maps, and others. One of the key features of our system is that tsunami inundations are estimated explicitly without any source information, which may contain large estimation error. Many calculations are performed in advance to investigate the sensitivities of the source models to coastal tsunami heights and inundation depth along the Pacific coast of Chiba prefecture in the Kanto region. We evaluate and improve our system through the demonstration experiments with local governments. We also validate the performance of the system for the simulated data as well as the observed data of the 2016 Fukushima-oki earthquake.

*J04-4-03
Joint Symposium / J04. Geohazard early warning systems

New Insights on Tsunami Genesis and Energy Source

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Conventional tsunami theories suggest that earthquakes with significant vertical motions are more likely to generate tsunamis. In tsunami models, the vertical seafloor elevation is directly transferred to the sea-surface as the only initial condition. However, evidence from the 2011 Tohoku earthquake indicates otherwise; the vertical seafloor uplift was only 3 - 5 meters, too small to account for the resultant tsunami. Surprisingly, the horizontal displacement was undeniably larger than anyone's expectation; about 60 meters at the frontal wedge of the fault plate, the largest slip ever recorded by in-situ instruments. The question is whether the horizontal motion of seafloor slopes had enhanced the tsunami to become as destructive as observed. In this study, we provide proof: (1) Combining various measurements from the 2011 Tohoku event, we show that the earthquake transferred a total energy of 3.1e+15 joule to the ocean, in which the potential energy (PE) due to the vertical seafloor elevation (including seafloor uplift/subsidence plus the contribution from the horizontal displacement) was less than a half, while the kinetic energy (KE) due to the horizontal displacement velocity of the continental slope contributed a majority portion; (2) Using two modern state-of-the-art wave flumes and a three-dimensional tsunami model, we have reproduced the source energy and tsunamis consistent with observations, including the 2004 Sumatra event. Based on the unified source energy formulation, we offer a competing theory to explain why some earthquakes generate destructive tsunamis, while others do not.

*J04-4-04
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Synthesis of Offshore Tsunami Records and Inundation Including Seismic Waves and Tsunami: Anticipated Nankai Trough Earthquakes, Southwest, Japan

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New tsunami observation networks such as DONET and S-net are designed for the observation inside earthquake focal area. When analyzing the tsunami recorded inside the focal area, seismic waves and tsunami appear at the same time. Theories that describe both seismic waves and tsunami are necessary. Saito and Tsushima (2016) proposed a method for synthesizing ocean-bottom pressure records considering both seismic waves and tsunami, but their method is not applicable to sea-surface displacement records. Recent observation enables us to observe tsunami by sea-surface displacement by using GPS buoys. Inazu et al. (2016) showed that real-time tsunami source estimation is possible if if we utilize high-precision, real-time GPS height observations equipped with cargo ships and tankers. This study shows a method that synthesizes tsunami records of sea-bottom pressure change and sea-surface displacement including seismic waves and tsunami. As examples of huge earthquake, the scenarios of anticipated Nankai-Trough huge earthquakes proposed by Hok et al. (2011) are used. By using their rupture scenarios as seismic sources in seismic-wave propagation simulations, we calculated spatial and temporal variation of the sea-surface displacement without considering gravity (e.g., Takemura et al. 2015). Then, we included the contribution of gravity by numerically solving tsunami equations and also simulated the inundation with high-resolution topography data using JAGRUS (Baba et al. 2015). Seismic waves and tsunami simultaneously appeared in both ocean-bottom pressure change and sea-surface displacement during the earthquake rupture, which would make tsunami analyses difficult. The seismic-wave contribution to sea-bottom pressure records is greater than to the sea-surface displacement. The data sets created in this study would be useful for practical tests of tsunami-prediction algorithms using offshore tsunami records, especially including the records inside the focal area.

*J04-4-05
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Rapid estimation of tsunami source location based on Tsunami Centroid Location (TCL) using NIED oceanfloor observation networks

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A rapid method of estimating tsunami source locations using real-time ocean-bottom hydrostatic pressure data from a dense offshore observation network has been proposed (Yamamoto et al., GRL, 2016). In this method, we calculate a characteristic location representing the real-time tsunami disturbance called tsunami centroid location (TCL), which is the centroid location of the maximum absolute amplitude of the real-time ocean-bottom hydrostatic pressure changes. The TCL could approximate the tsunami source centroid location, which is the weighted center of the absolute values of the initial sea surface height displacements and presents the approximate tsunami source location. In this presentation, we report whether the TCL can approximate the centroid location of the tsunami source by examining various near-field synthetic tsunami scenarios and several observed micro tsunamis from NIED oceanfloor observation networks; Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET) and the Seafloor Observation Network for Earthquakes and Tsunamis (S-net). In addition, we propose the method of real-time forecast for the arriving time on the target coastline using the TCL in order to issue the lead-time for citizens on the coasts.

*J04-5-01
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Tsunami data assimilation including effects of coseismic deformation for real-time tsunami forecasting using pressure gauges

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Recent developments of dense networks of ocean-bottom pressure gauges are expected to bring us highly reliable, fast warnings of tsunami attacks. Among wide variety of proposed methods for tsunami forecasting, data assimilation (DA) approach provides a successive estimation of tsunami wavefield rather than estimates of seismic source fault slip or initial sea height, which is suitable for real-time monitoring. The ocean bottom pressure gauge records, however, contain an offset due to coseismic deformation beneath the sensor. Here I propose a new method on the tsunami DA with separation of the coseismic deformation to estimate the true tsunami height.

In the original DA method, the pressure gauge data are directly assimilated to the shallow-water equation. The tsunami height at a step away is forecasted by numerical simulation, and the residual between forecasted and observed tsunami heights at the station location is used to assimilate the surrounding tsunami wavefield by the optimum interpolation kernel. Since the data assimilation uses the tsunami height estimated by pressure gauges, the assimilated tsunami wavefield should be contaminated by the coseismic deformation.

In the proposed method, we estimate the coseismic deformation in addition to the tsunami height. It is shown that the coseismic deformation can be approximately expressed as a solution of an inhomogeneous Laplace equation having pressure height as a source term. This equation is numerically solved for estimation of coseismic deformation term. A numerical experiment for this method with a real station layout was performed. By applying the proposed method to hypothetical observations, it correctly separated the coseismic deformation. It is noteworthy that the initial tsunami rise-up at very early time due to the coseismic deformation was clearly detected by this separation, which could be useful for shortening the necessary time for forecasting tsunami.

*J04-5-02
Joint Symposium / J04. Geohazard early warning systems

A fast tsunami data assimilation approach on the 2012 Haida Gwaii earthquake: based on the employment of Green's function

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Tsunami data assimilation has been proposed for tsunami hazard warning. It estimates the tsunami wave field by assimilating tsunami data observed offshore into a numerical simulation, without calculating initial sea surface height at the source. The Optimum Interpolation (OI) method is widely adopted in assimilating observed data. However, the traditional data assimilation approach requires quite large calculating time, because the forecasted waveforms are still calculated with tsunami propagation model for the entire region.

In this study, we present a new approach based on the employment of Green's function to improve the speed of data assimilation for tsunami warning. For the OI method, if the residual between observed and calculated tsunami height is not zero, there will be an assimilation response around the station. We consider the occurrence and linear propagation of such tsunami-height response as the ‘Green's function' of a station. Then the forecasted tsunami wave field can be calculated as the superposition of the Green's functions corresponding to different stations. Similarly, the observed tsunami data is repeatedly assimilated during the time window, and more Green's functions are superposed to the forecasted waveforms at Points of Interest (PoI).

This approach greatly reduces the time cost for tsunami warning because it no longer needs to run the tsunami propagation model, as long as the Green's functions are calculated in advance. It requires additional computer memory space for pre-calculated Green's function, but it does not have a significant impact on computational efficiency for regional-scale tsunami data assimilation. We apply our method to synthetic and real-time tsunami of the 2012 Haida Gwaii earthquake. The comparison with traditional data assimilation method reveals that this approach could achieve an equivalent high accuracy while saving much time for valid tsunami warning.

*J04-5-03
Joint Symposium / J04. Geohazard early warning systems

Evaluating the efficiency of a tsunami warning system to recover a tsunami source based on the r-solution method

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The mega thrust earthquakes quite often result in large tsunamis that may inflict a severe loss and pain to the population of the coastal communities. The development of the Tsunami Warning Systems is likely be the most constructive way in the mitigation of the destructive effect of potential tsunamis. To accurately forecast the inundation and run up in the near-field coast, where a warning should be issued in no more than 20 minutes, it is necessary to gain the insight into a tsunami source at the early stages of tsunami propagation. We offer a method for recovering a tsunami source and taking into account a particular arrangement of the monitoring system with respect to a tsunami source area and the sea bottom topography, we have developed the inversion method where the inverse problem operator was regularized by the least square inversion using the truncated Singular Value Decomposition approach. This method is based on the inversion of remote measurements of the water-level data without a priori information on a source but on their general spatial localization. Analyzing the singular spectra of a matrix obtained by numerical calculations one can estimate the subsequent inversion by a certain observational system that will allow offering a more effective disposition for the tsunami wave recorders by precomputations. The results obtained allow revealing the way to improve the inversion by selecting the most informative set of available recording stations. To avoid potential instability of the numerical solution, the r-solution method is used. This method seems to be attractive in view of computations since the main efforts are required for calculating the matrix to be obtained. In this study, we apply the approach proposed to evaluating the efficiency of a tsunami warning system to recover areal tsunami sources for the event of 6 February, 2013 near the Solomon Islands and for the event of 16, September, 2015 (Illapel, Chile).

*J04-5-04
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Improvement of tsunami-forecasting method based on tsunami inversion: small-size and large-amplitude tsunamis

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For more accurate forecasting of small-size and large-amplitude tsunamis, I improve the tFISH algorithm, which is a tsunami forecasting method based on offshore tsunami-waveform inversion for initial sea-surface height distribution. In the tFISH, initial sea-surface height distribution is expressed by a linear superposition of elementary tsunami sources each of which size is about 20 km. The size is small enough to resolve tsunami sources of moderate to large interplate earthquakes, but tsunamis that affect coastal communities are sometimes generated by a spatially small-size event such as a 2016 Nov. Mw 6.9 intraplate normal-faulting earthquake, occurring off Fukushima prefecture, northeastern Japan, and resulting in the 1.4-m-height tsunami at a coastal tide gauge. Because the source is comparable or smaller than that of an elemental source in the tFISH, the tFISH may not resolve the source and decrease accuracy of tsunami forecasting. To solve the problem, this study proposes a two-steps inversion. At the first step, the conventional tFISH inversion is performed. Then, we go to the second-step inversion when the following criterion is satisfied: the estimated source is expressed by extremely small number of elemental sources (e.g., one source only), meaning that the source may be unresolved image of the true source. At the second step, we perform tsunami inversion with elemental sources whose sizes are much smaller than the original. The elemental sources are distributed to sea area where tsunami source is imaged in the first-step inversion. Finally, we decide whether the second-step solution is chosen as the final solution using the following criterion: the comparison between observed tsunami waveforms and the calculations in the inversion shows the better agreement than in the first-step inversion. Numerical test assuming the 2016 off Fukushima earthquake shows the good performance of the new approach to avoid the unresolved tsunami source image.

*J04-5-05
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Near-field tsunami forecasting from offshore pressure data in association with the earthquake early warning

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Effective mitigation of tsunami disasters requires tsunami forecasts that are made in real time and the provision of timely evacuation warnings to affected communities. Tsushima et al. (2014) developed tFISH/RAPiD, which is the initial sea surface height distribution estimated from rapidly acquired GNSS data provides robust finite source size information that is incorporated into an offshore tsunami data inversion for reliable tsunami predictions along the near-field coast. In contrast, it is slightly difficult to obtain the reliable initial sea surface height distribution for M7 class earthquakes in the offshore region by RAPiD because of the difficulty of the accurate estimation of small coseismic displacement field compared with more large events.
Based on these backgrounds, we have developed an alternative algorithm that improves near-filed tsunami forecasting based on offshore tsunami data after an earthquake by incorporating earthquake early warning (EEW) data. Basic scheme is the same with the tFISH/RAPiD, we estimate the initial sea surface height distribution using the EEW data. We assumed that the single rectangular fault deduced from the scaling law between the earthquake magnitude and the fault dimension.
We retrospectively applied tFISH/EEW to the 2011 Sanriku-Oki earthquake (March 9, 2011, Mw 7.2) based on the actual ocean bottom pressure (OBP) record and EEW information. The predicted results immediately after the earthquake (~2 to 3 min) the arrival times and wave heights of the first tsunami wave along the near-field coast could be predicted more accurately than the estimation based only on offshore tsunami data. After more time, the estimated initial sea surface distribution by the tFISH/EEW had continuously changed, and it was similar to that based on offshore tsunami data alone.
We will discuss more detail characteristic and its ability of the tFISH/EEW algorithm based on the various case studies.

*J04-5-06
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Airborne observations with a nadir-pointing radar altimeter for a great tsunami detection

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Most tsunami forecasting systems rely on the predicted magnitude and epicenter of an earthquake. This system sometimes underestimates the tsunami, especially when the magnitude of associated earthquake is large and the tremor continues for a long time. Recent study reveals that satellite radar altimeters are capable of detecting tsunami (e.g., J. Gower, 2007), however real-time detection is still difficult due to the low frequency of sampling possessed by satellite systems. In this study, we suggest to detect tsunami directly by airborne radar altimeters.
We performed nadir pointing observations using Frequency Modulated Continuous Wave (FMCW) radar, which is attached to the bottom of an airplane body. The radar observation procedure is basically similar to the present satellite radar altimeter. However, in airborne observation, airplane altitude is changing by a few meters at any time during the flight. Thus, a precise prediction of airplane positions by Global Navigation Satellite System (GNSS) is also important. We estimated the position and altitude by a baseline kinematic analysis. We then estimated the averaged sea surface height (SSH) by the radar altimeter observation and the GNSS analysis result.
We conducted airborne observations once in June 2016, and twice in December 2016. To check the precision of SSH measurements, the flight days and paths were decided according to the satellite SSH altimeter Jason-2 and Jason-3 schedules so as to compare with their SSH data. After correcting the geoid and tidal changes, we confirmed that our observation error is less than 10 cm in average, which is sufficient to capture large tsunamis offshore. In the future, we expect to form a dense observation network by using multiple commercial airplanes equipped with the same radar altimeter, which enables real-time tsunami detections.

*J04-6-01
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Developing a Rapid Tsunami Response System: Application to South America Region

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Using high-performance computing and spatial information science, an advanced method of tsunami inundation forecasting and mapping can be developed to enhance real-time disaster response.
Given the maximum tsunami height and flow depth distribution, we perform quantitative estimation of exposed population using global population data, and the numbers of potential death by applying tsunami fragility curve. The prototype system under development is focused on South American region. In the trial operation, we verify the capability of the method as a new tsunami response system for three major tsunami-prone cities, Tumaco in the southern pacific coast of Colombia, Lima in the central coast of Peru, and Iquique in the northern coast of Chile. The bathymetry and topography data for the target cities were provided under the SATREPS project frameworks between Japan and the respective countries.
The tsunami simulation is based on the TUNAMI code developed by Tohoku University, Japan. The nested grid system for the bathymetry and topography data varies from 27 arc-second to 10 m resolution for the regional propagation and local inundation modeling, respectively. The global population data is taken form LandScan 2011 model. The mapping result and web publication are constructed using open-software, Generic Mapping Tools and Python Programing Language, respectively. The preliminary tests of the proposed system show promising result. The average total computational time for all regions is approximately 35 minutes.

The Operational Result for GEONET Real-time Analysis System for Rapid Finite Fault Modeling

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Geospatial Information Authority of Japan (GSI) has been continuously operating the REGARD (Real-time GEONET Analysis system for Rapid Deformation monitoring; for more detail see Kawamoto et al., 2017 in this symposium), which estimates earthquake fault model in real-time from 1-Hz GNSS observation, since 2015. REGARD has successfully observed the co-seismic displacements and estimated the finite fault model for some earthquakes of ~M7 since it ran.
Mainshock (M7.3) and two foreshock (M6.5 and M6.4, respectively) hit inland area of western Japan in the 2016 Kumamoto earthquake. The co-seismic displacements of about 100cm at most were observed from 1-Hz kinematic positioning, which was consistent with the result of GEONET F3 solution. REGARD system calculated that Mw of the mainshock is 6.85 in 58 seconds from event origin time. The final fault model of REGARD was estimated along the Futagawa fault zone within 6 minutes. This result is consistent with the evaluation by the Headquarters for Earthquake Research Promotion, which reports that the Kumamoto earthquake is considered to be mainly due to the activity of the Futagawa fault zone.
REGARD was able to detect the crustal deformation for other two earthquakes: one occurred at Tottori prefecture, western part of Japan, on 21th October 2016 (M6.6) and the other occurred off the Pacific coast of Tohoku region on 22th November 2016 (M7.4). However, the estimated finite fault model was slightly longer than the post-processed rectangular fault model by GSI for the case of Tottori, which led the overestimation of Mw, and the solution converted to the conjugate fault for the Tohoku because signal-to-noise ratio of GNSS kinematic positioning results were relatively small compared with the mainshock of Kumamoto earthquake. Further studies are needed to enhance the fault model estimation process for M6-7 class earthquakes, e.g. prepare more accurate initial condition and/or set multiple initial condition.

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Real-time multi-GNSS precise point positioning for earthquake and tsunami early warning over Asia-Pacific regions

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Real-time GNSS precise point positioning (PPP) is capable of measuring centimeter-level positions epoch by epoch at a single station, and is thus treasured in earthquake and tsunami early warning where static displacements in the near field are critical to rapidly and reliably determining the magnitude of destructive events. However, most operational real-time PPP systems at present rely on only GPS data. The deficiency of such systems is that the high reliability and availability of precise displacements cannot be maintained continuously in real time, which is however a crucial requirement for disaster resistance and response. Multi-GNSS, including GLONASS, BeiDou, Galileo and QZSS other than only GPS, can be a solution to this problem because much more satellites per epoch (e.g. 30-40) will be available. In this case, positioning failure due to data loss or blunders can be minimized, and on the other hand, positioning initializations can be accelerated to a great extent since the satellite geometry for each epoch will be enhanced enormously. This in turn will improve greatly the success rate of ambiguity fixing which, critically, plays as an indicative and guarantee of successful achievement of centimeter-level ground displacements. We established a prototype real-time multi-GNSS PPP service based on Australian national network which can collect and stream high-rate data from all five navigation systems above. We estimated high-rate satellite clock corrections and enabled undifferenced ambiguity fixing for multi-GNSS, which therefore ensures high availability and reliability of precise displacement estimates in contrast to GPS-only systems. We will report the preliminary performance of this service and analyze its potential to earthquake and tsunami early warning.

*J04-6-04
Joint Symposium / J04. Geohazard early warning systems

Real-Time Detection of Tsunami Ionospheric Disturbances with Stand-Alone GNSS Receivers

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Tsunamis can produce gravity waves that propagate up to the ionosphere generating disturbed electron densities in the E and F regions. These ionospheric disturbances are studied in detail using ionospheric total electron content (TEC) measurements collected by continuously operating ground-based receivers from the Global Navigation Satellite Systems (GNSS). Here, we present results using a new approach, also known as VARION (Variometric Approach for Real-Time Ionosphere Observation), and for the first time, we estimate slant TEC (sTEC) variations in a real-time scenario from GPS, Galileo, GLONASS and BeiDou constellations. Specifically, we study the 2016 New Zealand tsunami event using 1-Hz real-time data recorded from several GNSS receivers with multi-constellation tracking capabilities located in the Pacific region. We compare estimates of sTEC variations obtained using GPS, Galileo, GLONASS and BeiDou constellations. We observe sTEC perturbations with amplitudes up to 0.8 TEC units that correlate well in time and space with the propagating tsunami waves. The efficiency of the real-time sTEC estimation using the VARION algorithm has been demonstrated for the 2012 Haida Gwaii tsunami event. We conclude that the integration of different satellite constellations is a crucial step forward to increasing the reliability of real-time tsunami detection systems using ground-based GNSS receivers as an augmentation to existing tsunami early warning systems.

*J04-6-05
Joint Symposium / J04. Geohazard early warning systems

Inversion of tsunami and sea level uplift from GNSS-TEC: toward a breakthrough for tsunami monitoring systems?

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Ionospheric signals associated to atmospheric gravity waves generated by near and far field tsunamis are now routinely detected as well as acoustic waves generated by near-source ocean or solid earth uplift. Complete modeling of these signals can be done especially with solid/ocean/atmosphere coupled normal-mode summation which allows to model the tsunami amplitude not only in the ocean layer, but also in the atmosphere and ionosphere. This captures all the coupling and most of the physics of the propagation, including effects due to atmospheric local time, oceanic bathymetry and atmospheric wave attenuation.
We show here that 1D waveform inversions of the ionospheric signals model the tsunami sea levels variations with very high accuracy. These inversions based on tsunami normal-mode summations model the sea level vertical displacement close to the ionospheric piercing point of the GPS receiver-satellite pair and can therefore be compared to DART data. Inversions were therefore made for several tsunamis (2012 Haida Gwai, 2006 Kuril, 2011 Tohoku), in either far or near field. Statistics demonstrate the error of the inversion to be less than 10% of the peak-to-peak amplitude of the tsunami. These first results open important perspectives for densifying global tsunami monitoring systems, by offering tsunami height measurement in any fixed location equipped with a dual GPS system or even from mobile platforms, such as boats and aircrafts.
Recent modeling shows in addition that the acoustic pulse generated by large earthquakes not only reaches the ionosphere above the quake in less than 8-10 minutes, but provides a direct measurement of the vertical amplitude as well as the projection of the Earth or ocean affected surface.
These advances in the ionospheric inversions and the further developments of GNSS constellations will complement the existing surface seismic, geodetic and ocean systems and will likely improve future regional and global tsunami warning systems.

*J04-6-06
Joint Symposium / J04. Geohazard early warning systems

Possibility of real-time volcanic plume monitoring using GNSS phase residual and SNR data

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A volcanic explosion is one of the largest energy release phenomena on earth. The ash fall can seriously affect human activity. Thus, the monitoring and prediction of ash fall is very important. Unfortunately, visible light cameras cannot be used to observe eruptions that occur at night and/or when skies are cloudy. Several researchers have investigated the applicability of meteorological radar to the monitoring of the spatiotemporal distribution of eruption clouds, including the ash. Global Navigation Satellite System (GNSS) data provide a useful alternative to meteorological radar for detecting volcanic plumes (e.g. Ohta and Iguchi, 2015).
Recently, the GSI and Tohoku University have developed a nationwide (>1200 sites) real-time crustal deformation monitoring system (REGARD), based on kinematic GNSS analysis, to determine the coseismic fault model of large earthquakes. We will discuss the possibility of the real-time volcanic plume monitoring using GNSS phase residual and SNR data based on the REGARD system.

*J04-7-02
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Dynamic of aquifer compaction: Insight from continental-scale Sentinel-1 InSAR survey

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Overextraction of groundwater for decades has caused high rates of land subsidence in many plain aquifers of Iran. Geodetic measurements have been used in the past to study this problem in some of the major basins in Iran. Among them, Interferometric Synthetic Aperture RADAR (InSAR) has proven a powerful tool to obtain a regional overview of the extent and rate of displacement in a large scale. However, because the availability of regular SAR data acquisition was limited in the past, these studies are limited to some major plain aquifers.
After the launch of Sentinel-1, it is now possible to acquire SAR data regularly with large spatial coverage all over the world, providing the opportunity to produce displacement maps in continental scales. The purpose of this paper is to analyze elastic and inelastic deformation behavior of developed groundwater basins using large-scale Sentinel-1 InSAR. Using more than two years of data available in the archive of Sentinel-1 cyclic elastic deformations and continuous inelastic deformations induced by groundwater withdrawal are separated and the ratio between them is estimated for several aquifers. Moreover, the ratio between vertical and horizontal displacement is evaluated by decomposition of displacement maps derived from different look angles. Our results exhibit significant inelastic deformation behavior in major aquifers of Iran, which makes groundwater remediation measures a challenging task for depleted aquifers.

*J04-P-01
Joint Symposium / J04. Geohazard early warning systems

Real-Time Seismological Monitoring System in Northern Sakhalin

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Oil and gas are intensively exploited off-shore the Northern Sakhalin. Taking into account high level of seismic activity in the region and ecological risk of the corresponding infrastructure, permanent seismological monitoring is required. All the instrumentation and the monitoring system in a whole are designed in the Institute of the Physics of the Earth, RAS (Moscow, Russia). The final goal is to develop early-warning system to mitigate ecological risk. The system consists of 12 seismic stations, each equipped with three-component broadband velocimeter (T = 0.03 – 120 s) and accelerometer. The stations are spaced at about 20-30 km. Data is transferred to Khabarovsk, where the headquarter controlling all exploitation and transportation is situated. Data are automatically processed there in real time. The phase-picking is based on the STA/LTA algorithm. For tuning the algorithm of phase-picking, records are processed manually, in parallel. The system operates since September 2015. It is planned as a part of multi-component ecological early-warning monitoring system. Many hundreds of earthquakes are already parameterized and included in the catalogue. Strong-motion records are also obtained including records of felt earthquakes (intensity 4-5 MSK64 scale). Thus the system provides not only information for seismicity monitoring but also for engineering and future designing in the region.

An Earthworm based Earthquake Early Warning System with Integrated GMPEs and IPEs for Southwest Iberian Peninsula

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The South Iberian Peninsula is located near a complex plate boundary between Eurasia and Africa. Several very large earthquakes have occurred, especially offshore Cape San Vicente and in the Gulf of Cadiz. The largest one, the 1755 Mw 8.5 Lisbon earthquake, was associated with a destructive tsunami causing more than 60,000 casualties and significant damage in the SW Iberian Peninsula and NW Morocco (Buforn et al. 1998; Baptista et al. 2003; Gutscher et al. 2006; Grandin et al. 2007).
This study presents the development and results of a prototype of an Earthquake Early Warning System (EEWS) (Kanamori, 2005) in front of potentially destructive earthquakes occurring in Southwest Iberian Peninsula (Pazos et al., 2015), within the framework of the Alertes-Rim Spanish project. The existence of potential targets and recent events as 1962 Mw 6.2 and 1969 Mw 7.8, make this region suitable for the implementation of an EEWS.
This EEWS, based on the Earthworm (USGS) tools, was implemented to automatically produce location scenarios, with an optimized location and estimated magnitude that minimize the warning time (Romeu et al., 2016). Furthermore, the most suitable ground motion and intensity prediction equations, for this region, have been selected and integrated into the EEWS to provide potential damages scenarios.
Once the setup stage was over, the prototype was put into operation early 2015. Comparing to Instituto Geografico Nacional (IGN) catalog, hypocentral locations and magnitudes assessment are fairly good. Lead times obtained are on the order of tens of seconds for the majority of targets, which is long enough to mitigate damage for a big area of the southern coasts of Portugal and Spain, demonstrating the possibility of a regional, reliable and effective EEWS in the region.

*J04-P-03
Joint Symposium / J04. Geohazard early warning systems

Numerical shake prediction incorporating heterogeneous structure: the 2016 Kumamoto Earthquake

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Needless to say, heterogeneous structure, especially attenuation structure is important for ground motion prediction. In the new concept of real time ground motion prediction, called "Numerical Shake Prediction" proposed by Hoshiba and Aoki (2015), prediction of ground motion prediction is done by the estimation of current wavefield using data assimilation and simulation of wave propagation successively. We expected that the simulation with heterogeneous structure would improve the precision of ground motion prediction in the numerical shake prediction scheme. In this study, first we estimated the heterogeneous attenuation structure of the western part of Japan, then we evaluated the effect of the structure through the case of the 2016 Kumamoto Earthquake sequence.
To estimate intrinsic and scattering attenuation structure simultaneously, we conducted Multiple Lapse Time Window Analysis for the seismic stations distributed in the western part of Japan. Derived attenuation structure shows strong intrinsic and scattering attenuation around active faults and volcanoes in the Kyushu area. We derived tentative 2D velocity structure using the distribution of average apparent velocity of each station used in the MLTWA.
We conducted real time ground motion prediction simulation based on the numerical shake prediction scheme with heterogeneous structure for the Kumamoto Earthquake. In the case of 10 s ahead prediction, RMS of intensity prediction residuals improved by 15 % compared with the case of homogeneous structure. The rate of improvement became high in the 20 s ahead prediction. These fact shows the importance of considering the heterogeneous structure for the longer lead time.

Acknowledgment
We used waveforms observed by K-NET/KiK-net/Hi-net operated by NIED, the seismic network of Kyoto Univ., Kyushu Univ. and JMA. This study was supported by the Joint Usage/Research Center program of Earthquake Research Institute, the University of Tokyo.

*J04-P-04
Joint Symposium / J04. Geohazard early warning systems

Waveform matching for the ocean bottom pressure data toward real-time tsunami forecast

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Large-scale and dense ocean bottom observation networks have been maintained by NIED for regions along the Japan Trench (S-net) and along the Nankai Trough (DONET). To take an advantage of the ocean bottom observation network, we are developing a real-time tsunami forecast system including inundation for the Pacific coast of Chiba prefecture, using the real-time ocean bottom pressure data observed by S-net (Aoi et al., 2017). In this system, the several tsunami scenarios that reasonably explain the observed ocean bottom pressure data are selected according to the multi-index method (Yamamoto et al., 2016) from the pre-calculated database. The forecast information is generated from the coastal tsunami height and inundation information related to the selected tsunami scenarios. To advance the robustness of forecast and warning, it is better to implement several different approaches for real-time tsunami detection and forecast. In this study, therefore, we examine the matching for the time series of the ocean bottom pressure change at each station for selecting the tsunami scenarios that well explain the observation well using the simulated data for 150 S-net stations. When we use L1 and L2 norms to evaluate the fitness between the observed and scenario pressure data, the scenarios that give the smallest L1 and L2 norms do not provide the sufficient forecast result in the point that they underestimate the coastal tsunami height as well as the ocean bottom pressure data. This is probably because L1 and L2 norms are sensitive in the slight difference of phase information. Therefore, we pose the condition for the selected scenarios that the number of the stations where the maximum absolute amplitude of scenario is equal or greater than the observed one exceeds a criterion value before the evaluation according to L1 and L2 norms. This condition makes the waveform matching between the observed and scenario data better and the forecast result more satisfactory.

*J04-P-05
Joint Symposium / J04. Geohazard early warning systems

Development of semi-real-time tsunami calculation system for ocean-bottom pressure gauge stations in southwestern and northeastern Japan

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Ocean-bottom pressure gauge data are useful for detecting tsunami signals at suboceanic earthquakes and rapidly issuing warnings to coastal areas. We developed a semi-real-time calculation system that measures pressure perturbations at pressure gauge networks installed in offshore areas of southwestern and northeastern Japan (called DONET and S-net, respectively) in order to identify tsunami signals. The system automatically calculates geodetic deformations and tsunami propagation immediately after getting seismic source information on hypocenter, magnitude, and mechanism. The calculation area and grid size are categorized into four different areas and sizes, respectively, from the epicentral location of an earthquake to conduct an efficient calculation from the source to the networks. The calculation results for transoceanic tsunamis in a 7.5 arc-minute grid can be available in approximately 35 s after getting source information to output waveform data by executing the optimized parallel calculation code on our computer server. System operations began in July 2015 and have been applied to tsunamigenic earthquakes in the Pacific Ocean. The system is effective in identifying tsunami signals and automatically predicting tsunami propagation in offshore areas, which may be useful for further data analyses on tsunami propagation.

*J04-P-06
Joint Symposium / J04. Geohazard early warning systems

Sea level observations in the coasts of the Mexican Pacific of the tsunami caused by the 2011 Tohoku Earthquake

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The 2011 Tohoku earthquake (Mw 9.0) generated a powerful tsunami that traveled across the Pacific Ocean, reaching the western pacific on the American coastlines several hours after the initial shock. This event was registered in the 9 tide gauge stations that the Servicio Mareografico Nacional (Instituto de Geofisica, UNAM) had operating at the moment in the coasts of the Mexican Pacific: La Paz, Acapulco, Mazatlan, Huatulco, Puerto Vallarta, Salina Cruz, Lazaro Cardenas, Puerto Madero and Zihuatanejo. The data show that the first station to register the event was Puerto Vallarta at 19:10 UTC, 13 hours and 24 minutes after the earthquake, and the last station to register the perturbation was Puerto Chiapas at 22:06 UTC, 2 hours and 56 minutes later. The highest registered peak range was 3.22 meters in the station of Zihuatanejo, with a dominant period of the oscillations between 17 and 21 minutes, and a height above the tidal forecast of 1.38 meters. The data also show that in Acapulco the highest peak range was not reached during the first wave, it happened three and a half hours later, similar to what has happened with other remote tsunamis such as that generated by the 2014 Iquique earthquake. Thus, far-field tsunamis represent a hazard to our Mexican towns along the coastlines. The observations also suggest that some locations are prone to amplify the waves and could be initially neglected by small resolution forecast resulting from numerical simulations. Therefore, implementing regional forecast systems for remote tsunami events are suggested to alert and act on time against those remote events.

Decay Properties of Bay Oscillations Induced by the Tsunami of Nankai-Trough Earthquake

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In order to better understand the duration of tsunamis caused by large earthquakes, we investigate resonance responses of bays and their decay properties based on tsunami simulations for the Nankai-trough earthquake.

It has been reported that tsunami-induced oscillations in bays continue for a very long time, up to several tens of hours. For example, the tsunami warning of the 2011 Tohoku-Oki earthquake (Mw9.0) could not be canceled for two days after the earthquake. A good estimation of when tsunamis are settled is required for operations such as rescue, marine traffic, and coastal factories.

In this study, we examined the tsunami durations in bays based on the simulations for the eleven Nankai-trough earthquake source models provided by the Central Disaster Prevention Council (CDPC) of Japan. We focused on the tsunami properties in bays around the Tokyo bay, i.e., the Tokyo, Sagami and Suruga bays. The result of spectral analysis of the simulated waveforms confirmed that these bays have the same peak periodic component of period of ～70 min for the four of the eleven CDPC sources and T = ～80 min for the other seven sources. For all the eleven sources, a large component of T = ～110 min appears only in the Tokyo bay, implying that the component is the result of the resonance oscillation of the Tokyo bay.

We then investigated the decay time constant of each periodic component to understand the duration of the tsunamis that last in the bays. When the peak spectral period of T = ～70 min is generated in Tokyo bay, the average decay time constant is ～600 min for both components of T = ～70 and ～110 min. On the other hand, when the peak spectral period of T = ～80 min appears, the component of T = ～110 min has a longer decay time constant of ～800 min and that of the component of T = ～80 min is ～600 min. These results suggest that the decay property of each spectral component is not independent but interacts with each other.

*J04-P-08
Joint Symposium / J04. Geohazard early warning systems

Real-time correction of tsunami site effect by frequency-dependent tsunami-amplification factor

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For tsunami early warning, I developed frequency-dependent tsunami-amplification factor and used it to design a recursive digital filter that can be applicable for real-time correction of tsunami site response. In this study, I assumed that a tsunami waveform at an observing point could be modeled by convolution of source, path and site effects in time domain. Under this assumption, spectral ratio between offshore and the nearby coast can be regarded as site response (i.e. frequency-dependent amplification factor). If the amplification factor can be prepared before tsunamigenic earthquakes, its temporal convolution to offshore tsunami waveform provides tsunami prediction at coast in real time.

In this study, tsunami waveforms calculated by tsunami numerical simulations were used to develop frequency-dependent tsunami-amplification factor. Firstly, I performed numerical tsunami simulations based on nonlinear shallow-water theory from many tsuanmigenic earthquake scenarios by varying the seismic magnitudes and locations. The resultant tsunami waveforms at offshore and the nearby coastal observing points were then used in spectral-ratio analysis. An average of the resulted spectral ratios from the tsunamigenic-earthquake scenarios is regarded as frequency-dependent amplification factor. Finally, the estimated amplification factor is used in design of a recursive digital filter that can be applicable in time domain.

The above procedure is applied to Miyako bay at the Pacific coast of northeastern Japan. The averaged tsunami-height spectral ratio (i.e. amplification factor) between the location at the center of the bay and the outside show a peak at wave-period of ~20 min. A recursive digital filter based on the estimated amplification factor shows good performance in real-time correction of tsunami-height amplification due to the site effect.

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Revisiting the 1985 M8.1 Michoacan earthquake: Tsunami simulations and synthetic GPS data to test rapid response

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The 1985 Michoacan earthquake was a catastrophic event for Mexico. In terms of lives it had a toll of 10,000-20,000 casualties and the total economic cost was more than 5 billion dollars. The earthquake generated a local tsunami, which at the time did not generate much attention since most of the damage from the event was due to strong shaking in Mexico City. However, the extent of the tsunami was significant in the coast of Michoacan. In the industrial port city of Lazaro Cardenas, wave heights reached up to 2.5 m, with inundation distances of about 500 m. A segment of railroad of 1.5 km was destroyed and several fishing boats were reported missing. In Zihuatanejo, the impact was very similar and several beach front restaurants were washed away. In spite of this, at that time, in 1985, urbanization and development of the coastline was still somewhat sparse. However, much has changed in the intervening 30 years. We argue that the impacts from a repeat of an event such as this one would be much more significant today. The current population along the Mexican Pacific coastline has increased considerably and infrastructure has developed as well. Many locations have already suffered from flooding events during hurricanes and tropical storms, suggesting a rather high risk in case of a tsunami.

We use a published finite fault inversion for the earthquake and its largest aftershock as the initial condition of tsunami simulations and study the impacts along the coastline. Furthermore we generate synthetic high-rate GPS data for stations that exist today and show that the magnitude and extent of the earthquake could have been known within the first 60s of the event origin time. We show that rapid tsunami models that rely on these fast earthquake source products can provide useful forecasts of tsunami intensity in the first minutes after a large event.

*J04-P-10
Joint Symposium / J04. Geohazard early warning systems

REGARD: GNSS-based rapid finite fault modeling system

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We present a newly developed real-time GNSS system REGARD (the Real-time GEONET Analysis system for Rapid Deformation monitoring), which estimates single rectangular fault and slip distribution models within 3 minutes. The new system is part of the GNSS Earth Observation Network (GEONET) operated by Geospatial Information Authority of Japan, and it was developed in collaboration with Graduate School of Science, Tohoku University.

The REGARD system consists of real-time GNSS positioning, automatic detection of coseismic displacements by seismic events, and quasi real-time finite fault model inversion. The real-time data from the GEONET stations are processed by the RTKLIB (Takasu, 2013) and GSILIB (GSI, 2015) softwares. Then, the displacement time-series are monitored by RAPiD algorithm (Ohta et al., 2012) to detect earthquake events. If an early earthquake warning with M > 7 is issued and/or the displacement more than 10 cm occurred at neighboring 3 stations, the finite fault models are estimated from the coseismic displacement field.

The performance of the automatic inversions of the finite fault models is examined by using real raw GNSS data of the past large earthquakes: the 2003 Tokachi-oki earthquake (moment magnitude (Mw) 8.3), the 2011 Tohoku earthquake (Mw 9.0), and the 2011 off Ibaraki earthquake (Mw 7.7). A simulated 1707 Hoei-type Nankai Trough earthquake (Mw 8.7) is also tested. The Mw estimates with high variance reductions > 90 % were derived for all the earthquakes within 3 minutes. It is noteworthy that the Mw 8.83 was estimated for the 2011 Tohoku earthquake by 3 minutes without saturations. The performance assessment of REGARD confirmed that the real-time GNSS analysis is very powerful to estimate reliable Mw for large earthquakes with M > 8 rapidly.

*J04-P-11
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Accuracy of a continuous/on-demand GPS/Acoustic seafloor positioning using a slackly moored buoy in the Kuroshio region

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For the real-time detection of seafloor crustal movement associated with large earthquakes in a subduction zone, we have developed a continuous and on-demand GPS/Acoustic (GPS/A) seafloor positioning system using a slackly moored buoy, and tested the system over a year in Kumano-nada, Nankai Trough. In the system, the mooring cable length was designed to be 1.5 times the water depth (~3 km) for safety reasons against the strong Kuroshio current. The moored buoy usually drifts by wind and current within a circle of ~4-km radius around the array, which consists of six transponders forming a ~3 km triangle on the seafloor. Apart from the array center, large systematic error (> 1 m) arises in the positioning because of significant error propagation of the observation data (e.g. the buoy position, travel time) due to uncertainty of array geometry. To reduce the error, we redetermined the array geometry with 20-30 cm accuracy using new algorithm applied to campaign data. Using the revised array geometry, we compare final accuracies with automatic processed data on the buoy (realtime PPP and traveltime detection) and post-processed data (with precise almanac and manual waveform readout) for further improvement in the automatic algorithm. The former accuracy was 0.7/0.9 m in EW/NS component. In this presentation, we introduce the latter accuracy comparing the former one. Then, for further reduction of these error especially in the automatic procedure, we introduce our effort in the presentation to (1) determine again the array geometry using a new set of intense campaign data, (2) carefully evaluate the precision in real-time PPP using a precise moving table, (3) refine the traveltime detection algorithm against reflection from the surface.

*J05-1-01
Joint Symposium / J05. Crustal dynamics: Multidisciplinary approach to seismogenesis

Southern Costa Rica and the Next Decade: A Spatial and Temporal Opportunity for an International Subduction Zone Observatory

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A locked segment of the Middle America Subduction Zone surrounding Osa peninsula in southern Costa Rica has experienced large (Mw=7.2-7.4) earthquakes in 1856, 1904, 1941 and 1983. With an average recurrence interval of roughly 40 years and 34 years since the last rupture, the timing is right to instrument and record data of unrivalled importance before, during and after the next megathrust earthquake in this region.

The subducting young and anomalous (rejuvenated and thickened) lithosphere there, leads to shallow subduction. As a consequence, the plate interface beneath Osa peninsula lies 4 to 8 km beneath land where it is easily accessible for inland drilling. Furthermore, since the trench is only 20-30 km from the SW coastline of Osa peninsula, submarine cables with seafloor instrumentation, power and data transmission could be deployed and tight to borehole instrumentation, at a much lower cost than in other subduction zones.

The Costa Rica Volcanological and Seismological Observatory at Universidad Nacional (OVSICORI-UNA) is taking advantage of this great geographical and temporal opportunity to build and operate a dense geodynamic control network to record a wealth of data of unrivalled importance before, during and after the next megathrust earthquake in this region. With the growing interest for international subduction zone observatories, we invite the scientific community to joint efforts to fully capture the geophysical processes occurring in this subduction zone.

*J05-1-02
Joint Symposium / J05. Crustal dynamics: Multidisciplinary approach to seismogenesis

Spatio-temporal variation of the postseismic deformation of the 2011 off the Pacific coast of Tohoku Earthquake (M9.0) detected by means of terrestrial and seafloor observations

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Clear postseismic deformations are still being detected in terrestrial and seafloor geodetic observations on and around the Japanese Islands. Recently, Tomita et al. [2017, in Review] reported displacement rates at seafloor stations that were newly installed in 2012. We estimated displacement rates at the GNSS continuous stations at the Geospatial Information Authority of Japan and Tohoku University during the period from September 2012 to May 2016 (Period B). The same period in which Tomita et al. [2017] estimated displacement rates at the seafloor stations. Taking a trench-normal profile that runs through the main rupture area of the Tohoku Earthquake, in the forearc region, the trench-normal displacement rates during Period B were as large as one fourth of those during the period from April to December 2011 (Period A). In contrast, the differences between the vertical components in Periods A and B are very clear. The large local subsidence around the Ou Backbone Range observed in Period A had almost vanished in Period B, while the uplift rates in Period B were more than half those in Period A. The low viscosity beneath the Ou Backbone Range hypothesized by Muto et al. [2016] to account for the large local subsidence, also accounts for the rapid decay of local deformation. Because the inland rheological heterogeneity strongly affects the vertical displacement rate field, we estimated the distribution of interplate coupling and postseismic slip based only on horizontal displacement rates and applying Sun et al. [2014]'s model to exclude the effects of viscoelastic relaxation. Preliminary results indicate that postseismic slip occurred at the shallow plate interface off the Fukushima and Ibaraki Prefectures and at the deep portion beneath the Pacific coast of the Iwate Prefecture during Period B, the same as Period A. Estimated back-slip in the main rupture area of the 2011 Tohoku Earthquake indicates interplate coupling at the area has already recovered.

*J05-1-03
Joint Symposium / J05. Crustal dynamics: Multidisciplinary approach to seismogenesis

Stress field around fault zones of the 2016 Kumamoto earthquake sequence (Mj7.3) inferred from moment tensor data from 1996 to 2016

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The 2016 Kumamoto earthquake sequence started from 14 April 2016 in Kumamoto prefecture, middle part of Kyushu Island, Japan and involved the largest event with magnitude of 7.3 occurred on 16 April 2016. Events over M 6 also occurred before and after the mainshock. High background seismic activity observed in this area before the earthquake occurrence. Inelastic strain distribution in the area estimated by seismic moment tensor data implies that the major events of the sequence occurred “around" large strain region. This suggests that the large inelastic strain created stress concentration. In this study we analyzed the seismic moment tensor data before and after the occurrence of the sequence and estimated stress field in the hypocentral area. As general tendency, dominated minimum principal stress (sigma 3) in the N-S direction obtained and the maximum principal stress takes value close to the moderate one. The stress field reveals spatial heterogeneous feature, which varies from southern to northern part of the area. We found that the stress field around the fault zone is consistent with co-seismic fault behavior of the earthquake sequence and decreasing maximum horizontal stress. The results shows that complex co-seismic rupture and the seismic activity associated with the sequence could be attributed to the uniaxial extension of deviatoric stress field.

*J05-1-04
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Effects of Postseismic Stress Redistribution of the 2011 Tohoku Earthquake on Fault Activities

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The postseismic deformation and seismicity following the 2011 Mw9.0 Tohoku-Oki earthquake have been recorded at unprecedented spatial-temporal resolution. Taking advantage of these observations, we have refined our published three-dimensional (3D) viscoelastic finite element models to study the evolution of the stress field following the 2011 earthquake. The model incorporates the first-order 3D structural heterogeneity in NE Japan which includes the subduction of the Pacific and Philippine Sea plates, and the laterally-heterogeneous and depth-layered rheological structure of the upper mantle. We assume that the upper mantle is characterized by a bi-viscous Burgers rheology. Our preferred model well reproduces the first-order pattern of the five-year GPS observations of the postseismic crustal deformation in both horizontal and vertical directions. We calculate postseismic Coulomb stress perturbations (CSP) on published known crustal faults as well as over nodal planes of earthquakes from focal mechanism data. Overall, thrust faults tend to undergo stress decrease after the 2011 earthquake while normal and strike-slip faults tend to undergo stress increase. After the 2011 mainshock, events in the forearc and near the rupture region of the subducting slab underwent generally CSP decrease, while the events downdip of the 2011 rupture experienced generally CSP increase. The outer rise of the Pacific plate underwent CSP increase.

*J05-1-05
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Modeling deformation processes of the island arc crust and mantle during the postseismic period of the Tohoku-oki earthquake

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This paper investigates postseismic viscoelastic deformation in the island arc crust and mantle and postseismic slip of the Tohoku-oki earthquake considering the heterogeneous rheological structure. We first calculated the effective viscosity distribution of the Japanese island arc crust and upper mantle. Then, we calculated the viscoelastic deformation of the Japan island arc during the postseismic period of the Tohoku-oki earthquake considering the coseismic slip distribution obtained by our inversion analysis using a finite element method. After removing the viscoelastic deformation from the observed displacement data, we performed inversion analysis to obtain postseismic slip distribution. For calculation of the effective viscosity distribution of the Japanese island arc crust and upper mantle, we first considered the thermal structure obtained by dense geothermal observations from Hi-net boreholes (Matsumoto, 2007) and by Tanaka et al. (2004). The model could not reproduce well a postseismic strain anomaly (decreases in areal strain) along the volcanic front after the 2011 Tohoku-oki earthquake, which was found by Miura et al. (2014). Therefore, we considered local low viscosity region beneath volcanoes. In this case, a postseismic strain anomaly (decreases in areal strain) along the volcanic front can be reproduced. We also obtained postseismic slip by the inversion analysis. The results indicate large postseismic slip occurred below the deeper part of the coseismic slip region. We test several viscoelastic structures and report a model which explains well the postseismic deformation in the inland region of northeastern Japan.

Frictional strength of plate interfaces inferred from numerical simulations of stress fields for oceanic plates: Application to the North American-Pacific plate interface off northeast Japan

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Steady plate subduction along a curved interface brings about stress changes at constant rates in the surrounding lithosphere (Fukahata and Matsu'ura, 2016). So, in subduction zones, not only frictional resistance at plate interfaces but also steady plate subduction causes tectonic stress fields. The stress field caused by frictional resistance is basically compressive, but that caused by steady plate subduction is basically tensile in a seismogenic depth-range. Comparing these stress patterns with the actual tectonic stress fields, we can obtain information about the absolute frictional strength of plate interfaces on the same idea as Terakawa and Matsu'ura (2009).
In northeast Japan, the Pacific plate is descending beneath the North American plate. Before the 2011 Tohoku-oki earthquake, the focal mechanisms of seismic events at and around the plate interface were thrust-fault type (e.g., Asano et al., 2011), indicating that the compressive stress field due to frictional resistance was dominant there. The drastic increase of normal-fault type events after the Tohoku-oki earthquake could be interpreted as the change in stress regime from compression to tension. In this study, we estimate the lower limit of frictional strength at the plate interface through the 2-D numerical simulations of stress fields for descending oceanic plates. The advantages of oceanic plates are, it passes through the plate-to-plate interaction zone within a limited time (1-2Ma), and its rheological property is much simpler than the overriding plate (Matsu'ura et al., 2017 JpGU-AGU Joint Meeting). The results of numerical simulations show that the tensile stress in the upper part of the oceanic lithosphere reaches 200 MPa at the depth-range of 10-20km. We will show the downdip variation of frictional strength to reproduce the pre-seismic compressive stress field at and around the plate interface.

*J05-2-01
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A unified representation of Earth's quasi-dynamic deformation processes

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The last three decades have witnessed an explosion of studies on fault processes, from kinematic modeling of geodetic data to dynamic modeling of fault rheology. These studies were made possible by fundamental solutions that describe the stress and displacements caused by slip on a fault. In contrast, direct imaging of the kinematics of off-fault deformation is still impractical, and the dynamic modeling of anelastic deformation still relies on computationally intensive numerical methods (e.g., Barbot & Fialko, 2010). Here, we describe a novel approach that allows us to resolve distributed processes in kinematic inversions of geodetic data and to incorporate off-fault processes in numerical models of earthquake cycles. We quantify analytically the displacement and stress incurred by distributed anelastic strain in finite shear zones (Barbot, Moore & Lambert, BSSA, 2017). We use these elementary solutions to simultaneously invert for slip on faults and distributed strain in the surrounding rocks. We apply this new technique to study postseismic relaxation following the 2016 Mw 7.0 Kumamoto, Japan earthquake (Moore et al., 2017). We directly image the spatial distribution of effective transient viscosity in the Kyushu lower crust, revealing the systematic variations associated with the volcanic arc and plutonic bodies. Our formulation also allows the dynamic simulation of earthquake cycles with distributed deformation using the integral method, an approach more accurate and many orders of magnitude faster than classic finite-element techniques. We simulate earthquakes cycles within the lithosphere-asthenosphere system using rate-and-state friction and the power-law flow of olivine (Lambert & Barbot, 2017), revealing the prevalence of viscoelastic flow in the early stage of postseismic relaxation. Our approach will be instrumental in building comprehensive physical models of stress evolution at plate boundaries.

*J05-2-02
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Rheological Structure Beneath Java Island after the 2006 Java Tsunami Earthquake Based on GPS Data

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We determine postseismic deformation associated with the 2006 Java tsunami earthquake using Global Positioning System (GPS) data located in Java Island. By using an analytical approach of logarithmic and exponential functions, we find decay time in the order of hundred days after the mainshock as observed by eight years data after the mainshock. This result suggests that decay time for magnitude 7 class tsunami earthquake is longer than a general megathrust earthquake event for similar magnitude. In our postseismic deformation analysis, we investigate the contribution of aftersip and viscoelastic relaxation of the 2006 earthquake. We also calculate the effect of using different coseismic fault to the viscoelastic relaxation. By simultaneously calculate viscoelastic relaxation and afterslip, our result of best-fit rheological model comprises a 60 km elastic layer thickness with a viscosity of 2.0 x 1e17 Pa·s in the asthenosphere. We also find that afterslip contribute of more than two-thirds (~80%) of horizontal displacements in the GPS data, in which asesimic slip occurred at deeper part of the coseismic rupture.

*J05-2-03
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Afterslip and Viscoelastic Relaxation Model Following The 2010 Mentawai Earthquake Deduced from Postseismic Surface Deformation

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Sumatra, Indonesia, is an island of high tectonic activity due to the northeastward subduction of the Indo-Australia beneath the Eurasian Plates at a rate of ~60 mm/year. This plate convergence causes high seismic activity in the region, and the M7.8 Mentawai earthquake on October 25th, 2010 is just one of those. We study its postseismic viscous relaxation in the upper mantle using geodetic data along the Sumatra subduction zone. Previous studies found that both afterslip and viscoelastic relaxation are responsible for the observed postseismic deformation (e.g. Gunawan et al., 2014). The two mechanisms have different temporal and spatial domains (Wang, 2007). Afterslip occurred up- and down-dip segments of the coseismic fault rupture and generated a crustal deformation in short to medium periods (e.g. Hsu et al., 2002; Freed, 2007). On the other hand, viscoelastic relaxation dominates the deformation over the larger area and the longer period (e.g. Wang et al., 2001; Pollitz et al., 2006).

The analysis in our previous study of the first two years of postseismic surface deformations revealed that afterslip contributed significantly to the postseismic deformation. We first modeled the deformation by the viscoelastic relaxation and isolated the afterslip contribution by subtracting the model from the data. Then we estimated the afterslip distribution on the plate interface. According to Ardika (2015), afterslip caused by the 2007 Mentawai earthquake can be modeled using a logarithmic function and continued for about a half year after the mainshock.

Keywords: Earthquake cycle, Postseismic deformation, Viscoelastic Relaxation, Afterslip

Reciprocal relationship between seismically estimated slip rates and geodetically estimated slip-deficit rates at plate interfaces: Physical interpretation and logical consequence

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Repeating earthquakes, the sequence of stress accumulation and release at isolated small asperities on a plate interface, can be regarded as a renewal process in statistics. From such a point of view, we modeled a sequence of repeating earthquakes and developed an objective Bayesian method to estimate the space-time distribution of interplate slip rates from the recurrence intervals of repeating earthquakes. Appling this method to the complete data set of repeating earthquakes in northeast Japan for 18 years before the 2011 Tohoku-oki earthquake, we revealed spatiotemporal variations of interplate slip rates (Nomura et al, GJI 208, 2017). For a seismically calm period (1996-2000), we compared the average slip-rate distribution estimated from repeating earthquake data with the average slip-deficit-rate distribution estimated from GPS array data (Hashimoto et al., GJI 189, 2012), and found good reciprocal relationship between their spatial patterns. What we can estimate from repeating earthquake data is the background slip rates for small asperities. On the other hand, what we can estimate from GPS array data is the slip-deficit rates of underlying large asperities. So, the sum of the slip rate and the slip-deficit rates should be equal to a plate convergence rate, but the actually estimated slip rates are a bit small to satisfy the above postulation. This may be responsible for the empirical relation between recurrence intervals and magnitudes of repeating earthquakes (Nadeau & Johnson, BSSA 88, 1998), which scales the amplitude of slip rates. If we use a theoretical relation instead of the empirical one, the above postulation, which suggests a hierarchic structure of asperities, is well satisfied.

*J05-2-05
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Characteristics of spatiotemporal variation of hypocenters and the diversity of waveforms of deep low-frequency earthquakes in northeastern Japan

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We have investigated the characteristics of spatiotemporal variation of hypocenters of deep low-frequency (DLF) earthquakes in northeastern Japan using the earthquake catalog of the Japan Meteorological Agency, and relocated hypocenters by the hypoDD method. DLF earthquakes are believed to occur by another mechanism than the fault motion because they occur below the depth of brittle/ductile transition. However, the mechanism is still unknown. Thus the comparative study of spatiotemporal variation of hypocenters and waveform characteristics among many source areas is important to clarify the source process of DLF earthquakes.
We found that the thickness of the seismogenic layer of DLF earthquake varies in space at distances of 100–250 km. We also found that the areas with nearly constant seismicity have a spacing of 100–150 km. These values are several times larger than the spacing of hot fingers that correlate well with areas of low-velocity anomalies in the Tohoku district. No clear temporal change of seismicity of DLF earthquakes was found after the 2011 Tohoku-Oki earthquake, which suggests a small change in the stress at the source depths of DLF earthquakes.
We next examined the diversity of waveforms of DLF earthquakes by grouping the events using waveform cross-correlation. In a time window just after S-wave, closely located earthquakes tend to form a single group, which suggest the similarity of focal mechanisms among the grouped events. However, the values of cross-correlation are much lower than those of ordinary high-frequency events. This suggests that the focal mechanisms and/or source process of DLF earthquakes are different from event to event. In time windows of later phases, the correlation take lower values and the grouped events were not colocated. Thus the later phases have less information of source mechanism than S-wave, which should be considered for the source study by waveform modeling.

*J05-3-01
Joint Symposium / J05. Crustal dynamics: Multidisciplinary approach to seismogenesis

Spatial heterogeneity of crustal stress

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It has long been believed that crustal stress is highly heterogeneous in space. Direct stress measurements in boreholes show that directions of the maximum compressional stress axis change in location, from a borehole site to another, or even within a same borehole. These measurements imply that crustal stress is fractal. Heterogeneous slip distributions and hypocentral distributions are explained by heterogeneous stress fields. Stress inversion studies of focal mechanisms reveal that estimated stress field changes in space and also in time. Recently, it is reported that directions of the maximum compressional stress axis change before and after large earthquakes. These phenomena are usually explained by small magnitudes of differential stress (maximum minus minimum compressional stress) in focal regions However, the estimated magnitudes are too small compared with those estimated from frictional experiments, thus an alternative explanation is that they reflect heterogeneous stress field. They assume that crustal stress is highly heterogeneous and acts on each fault in a direction to which the fault easily slips. Namely, faults of a different orientation are subjected under different stress field. When slips of large earthquakes generate stress changes, only faults that are favorable for those stress changes can be triggered by the stress changes, and an apparent stress field could be estimated by stress inversions using only those triggered earthquake data.
In this study, we will try to reveal that crustal stress is regarded as uniform in a km scale from stress inversion analyses of focal mechanism, different from the usual idea of a fractal-like stress field. We analyze precise focal mechanisms and do a simple simulation of crustal stress considering heterogeneous structures.

*J05-3-02
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Fault rocks and paleostress fields in the San-in shear zone, western Japan

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Recent geodetic study revealed that the strain rate in the San-in Region is actually high and this active region of deformation is called ‘the San-in shear zone'. The San-in shear zone almost overlaps with the San-in seismic zone and the some inland earthquakes (the 2000 Western Tottori earthquake and the 2016 Central Tottori earthquake) occurred in the San-in shear zone. To understand the crustal deformation in the shear zone, the Crustal Dynamics project has planned very high-density seismic observation of seismograph in 1000 point around aftershock area of the 2000 Western Tottori earthquake. On the other hand, it is important for us to reveal the distribution and characters of fault rocks around aftershock area and compare paleostress field in the past with that in the present day.
Recent geologic study around aftershock area of the 2000 Western Tottori earthquake revealed that the distribution of faults around aftershock area was concordant with the aftershock distribution and explained the relation between the geometry of the source fault and inactive fault.
In this study, We estimated paleostress fields formed inactive fault in granitic rocks around aftershock area by the Hough-transform-based stress tensor inversion method (Yamaji et al., 2006; Sato and Yamaji, 2006). First, I estimated paleostress fields of each faults having fault gouge or cataclasite as characters of fault rocks. As the result, two stress tensors were detected with strike-slip faulting regimes from faults having fault gouge. One is consistent with the present stress field in SW Japan. On the other hand, three stress tensors were detected with reverse and normal faulting regimes from faults having cataclasite.
With respect to different paleostress fields, fault system around aftershock area was formed by stress fields with reverse and normal faulting regimes in the past seismogenic zone and by stress fields with strike-slip faulting regimes in shallow depth with low confining pressure.

*J05-3-03
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Three-dimensional seismic velocity structure beneath the northern South Island, New Zealand from dense seismic observation

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The northern South Island of New Zealand straddles the plate boundary between the Australian and Pacific Plates and is a transition zone between the Hikurangi subduction margin and a continental transform system, with the Alpine Fault as its principal component. The Alpine Fault separates two distinct tectonic provinces. To the SE lies the Marlborough system of dextral strike-slip faults (MA faults), while to the NW lies an area of active compressional inversion where inherited normal faults are reactivated predominantly as steep reverse faults (e.g. Buller-Nelson area - BN faults). In this study, we image the seismic velocity structure beneath the shallow seismogenic zone for both the eastern MA faults and the western BN faults. A temporary dense seismic observation network was deployed in the northern and central parts of the South Island, New Zealand. We use data from these temporary stations (51 stations), acquired from March 2011 to April 2015, together with data recorded by the New Zealand GeoNet network (22 stations). For the analysis we also include data from the aftershocks of the 2016 Kaikoura earthquake, recorded by GeoNet. Total number of located earthquakes is 5389. We employed the Double-Difference Tomography Method to relocate hypocenters and estimate the seismic velocity structure. The results from the seismic tomography show low-Vp, Vs and a high Vp/Vs zone beneath the epicenters in the NW South Island. The high Vp/Vs area seems to be continuously distributed from the upper surface of the subducted crust to the bottom of the shallow seismic active area in BN faults. We also see seismic low-velocity area in and beneath the hypocenter and the focal area of the 2016 M7.8 Kaikoura earthquake. These observations suggest that fluid from the subducting plate weakens the crust and promotes the occurrence of earthquakes in this area.

*J05-3-04
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3d distribution of fluids and their origins in a seismogenic zone, Northern Miyagi, NE Japan

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Northern Miyagi is a seismically active region located in one of the strain concentration zones in NE Japan. This area experienced three large earthquakes, in 1900 (M7.0), 1962 (M6.5) and 2003 (M6.2). The 2003 earthquake was well studied and its focal mechanism and aftershock distribution support that the earthquake was a high angle reversed fault, which is a reactivation of an originally normal fault, created in the Miocene during the Japan opening. Geologically, the area is mostly simply covered with thick sediment and is surrounded by granitic rocks of Kitakami Mountains to the east and to the north. The objectives of this study are to image the geofluid in three dimensions using magnetotellurics (MT) and to relate them to earthquake activities in the region.
We used MT data at 67 sites in total, covering 50km x 50km area. 39 sites are new and 32 sites are from the compilations of the previous three MT profiles in the area (Nagao, 1997; Mitsuhata et al, 2001; Sato et al., 2005). The previous profile data were inverted assuming the structure is quasi-two-dimensional, but we have found strong three-dimensionality in the dataset. We inverted the data using 3d inversion code, WS3dMTINV (Siripunvaraporn and Egbert, 2009). The model showed three deep conductors around the focal depths of the three large earthquakes. This suggests that high pore pressure fluid is episodically expelled from the reservoir to induce earthquakes in a less permeable zone..
Current high seismicity is seen at the outer rim of the deep conductors. The northernmost conductor at 1962 earthquake has a deeper extension to northwest toward Kurikoma volcano. However the conductors at 1990 and 2003 earthquakes have no deeper extensions. The former conductor at 1962 earthquake implies fluid supplied from the volcanoes. In contrast, the latter conductors at 1990 and 2003 earthquakes imply fluids trapped in sediment at the rim of the Miocene rift.

A new temperature proxy on faults during earthquake by using maturity of carbonaceous materials: Kinetic effect on the maturation

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Quantitative estimation of frictional heat produced in the fault zone (i.e., maximum temperature) is one of the keys to estimate the slip behaviors of earthquakes. Irreversible thermal maturation reaction of carbonaceous materials, which is very sensitive to maximum temperature, is reported to be a great indicator for frictional heat recorded in fault rocks. In fact, such maturation process could be strongly affected not only by maximum temperature but also by heating rate. However, previous studies have conducted under the heating rate of ~1 degree per second, which is markedly lower than that during earthquake slip (several tens to several hundreds of degrees per second). Here we performed new heating experiments at two different heating rates (~1 and ~100 degrees per second) by using carbonaceous material sampless retrieved from an ancient plate-subduction fault. We then carried out IR and Raman spectroscopic analyses and py-GC/MS analysis to characterize the degree of the maturation. The samples after high heating rate of 100 degrees per second showed relatively low maturation than those after 1 degree per second-heated samples. Thus, heating rate is one of the important factors to estimate the maximum temperature recorded in the faults, and our results could indicate that previous researches underestimate the temperature.

GPS VELOCITY FIELD IN THE NORTHWESTERN CORNER OF SOUTH AMERICA

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Global Positioning System (GPS) data from southern Central America and northwestern South America collected at GPS permanent stations during the last ten years reveal wide plate margin deformation along a 1400 km length of the North Andes. Associated with the oblique subduction of the Nazca plate at the Colombia-Ecuador trench is the “escape" of the North Andes block (NAB). This work presents and discusses a new horizontal velocity field for northwestern South America derived from CORS (Continuously Operating Reference Stations) GPS observations of geodetic networks located in Colombia, Panama and Ecuador. In Colombia, the GeoRed network is a dedicated GNSS network for geodynamic studies installed by the Colombian Geological Survey through the Space Geodesy Research Group that currently consists of 100 stations. In this work, we use data from GeoRed permanent stations with a minimum of 2.5 years of observations. Using GPS velocity vectors for 53 permanent stations, we have estimated a new regional geodetic velocity field. We used an updated model for the present-day angular velocity of the South American plate (SEGAL model) based on a much denser network of CORS velocity solutions (Fernandes et al., in prep.). We combined our velocity field with the published results of Nocquet et al. (2014), to provide a more complete picture of velocities across the entire North Andes block. Nocquet et al. (2014) used a large number of sites in Ecuador, with only a few sites in Colombia, so the two data sets are highly complementary. They defined the stable South American plate using a different set of sites than used in the SEGAL model, so we used the four overlapping sites between the two data sets, all located in northern Ecuador or southern Colombia, to compute the offset between the two South America frames. We then estimate the motion of the North Andes block using a subset of these sites, and investigate tectonic motions relative to the North Andes block.

*J05-4-02
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Taiwan vertical velocity field from precise leveling observations, 2000-2015

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The active Taiwan mountain belt is located at the plate convergence boundary between the Eurasian plate and the Philippine Sea plate. Therefore, a high accuracy vertical velocity field is very important to understand the on-going mountain building mechanism and the earthquake potential of reverse faults. The precise leveling is always the best way to obtain the high accuracy vertical velocity field until now even though it has the limitation of high field surveying cost. In this study, five precise leveling measurements during 2000-2015 from a whole-island leveling network including 2137 benchmarks were used to infer a high accuracy vertical velocity field in Taiwan. First, the systematic errors of the leveling observations listed in the specification of first-order leveling were corrected. Second, the leveling network adjustment of which was minimum constrained to the orthometric height of K999 benchmark was estimated to obtain the orthometric height of the benchmarks distributed in the main roads of Taiwan. The slope-dependent errors of the leveling observations were also analyzed in this study. By means of the coordinate time series analyses and the accommodations of the effects of coseismic displacements, the vertical velocity of each benchmark was estimated by Least-squares Estimation (LSE), respectively. Finally, a GNSS-derived surface vertical velocity field in Taiwan, 2000-2015, was used for the comparisons to examine the performance of the leveling-derived one in this study.

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Observation of aseismic crustal deformation in Taiwan by analysis of InSAR and GPS data

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In this study, we report aseismic crustal deformation detected by InSAR images and GPS data in southwestern Taiwan where is characterized by high convergence rate and very low seismicity. GPS observation network has been well established there, which is preferable to correct noisy interferograms. We use SAR data of L-band satellites (ALOS and ALOS-2) to obtain coherent images even for dense forests. After removing long wave-length noise and height dependent term from interferograms using the GPS velocity field (Tsai et al, 2015) and DEM, we stacked the corrected interferograms for further noise reduction. Using these images, we derived the quasi-vertical and quasi-east velocity fields. We found very rapid uplift in the area stretching about 25 km in the N-S direction with about 5 km E-W width. The uplift rate increases from south to the north, and it shows step-wise change in the eastern flank. Ching et al, (2016) reported up to 20 mm/yr uplift rate detected by leveling survey passing through the southern part of the uplift area. The quasi-uplift rate obtained by InSAR at the southern part is consistent with those given by leveling survey. On the other hand, the maximum uplift rate detected by InSAR reaches up to 45 mm per year at the northern part, twice as large as the rate along the levelling route. Judging from very low seismicity in this region, the severe crustal deformation we detected with InSAR is aseismic.
The 2-D distribution of whole uplift rate seems impossible to explain only by fault motion, and mud diapir should be another important factor. We found a sharp displacement discontinuity in the coseismic interferogram of the Meinong earthquake (M6.4), which implies that the aseismic uplift is mainly driven by the mud diapir, but the shallow active fault works as a pre-existing weakness.

*J05-4-04
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Rapid crustal deformation in SW Taiwan caused by the interaction between active faults and reactivated mud diapirs

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The geodetic data from 2002 to 2016 and 17 ALOS SAR images between 2007 and 2011 were collected in this study to understand the rapid surface deformation in SW Taiwan. The geodetic data comprise 35 dual-frequency and 9 single-frequency continuous GPS stations, 65 campaign-mode GPS stations between 2002 and 2015 and 10 precise leveling routes between 2010 and 2016. All surface velocities are relative to the Chinese continental margin. From north to south, three regions (HLVRs) with extremely high line-of-sight velocity of larger than 40 mm/yr were identified in SW Taiwan. Two of them (middle and southern HLVRs) are located within the central gap between two NE-SW-striking faults, which are the Lungchun fault (LCNF) to the west and the Chishan fault (CSNF) to the east. An uplift rate of ˜80 mm/yr is detected at the middle HLVR. At the middle HLVR, a shortening rate of ˜47 mm/yr and a left-lateral rate of ˜6 mm/yr are shown across the LCNF, while an extension rate of ˜32 mm/yr, and a right-lateral rate of ˜11 mm/yr are represented across the CHNF. For the region south of the southern HLVR, a shortening rate of ˜2 mm/yr and a right-lateral rate of ˜10 mm/yr are shown across the LCNF, while a shortening rate of ˜3 mm/yr, and a left-lateral rate of ˜1 mm/yr are presented across the CHNF. Therefore, the middle HLVR is moving toward NE while the southern HLVR is moving toward SW. After comparing with the locations of mud diapirs and the seismic reflection profiles in SW Taiwan, we proposed that these three isolated HLVRs are the ongoing active inland mud diapirs. The overpressured sediments and fluid are squeezed and pushed upward due to the tectonic compression. Because these inland mud diapirs are bounded by the active faults, the materials are also extruded toward the free boundaries along the channel constructed by these faults.

*J05-4-05
Joint Symposium / J05. Crustal dynamics: Multidisciplinary approach to seismogenesis

Performance of VADASE single-frequency GPS solutions in the 2016 M 6.5 Meinong, Taiwan, earthquake

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The 6 February 2016 MW 6.5 Meinong earthquake produced widespread strong shaking with 30-85 cm/s Peak Ground Velocity (PGV) in the 30-km-away Tainan city, where we installed eight 1-Hz single-frequency (SF) and one dual-frequency (DF) GPS stations about 4 month before the earthquake. The observed PGVs are significantly higher than the near-fault ground motion collected from moderate-sized earthquakes occurred worldwide and caused about 10 buildings collapsed and 117 death in the Tainan city. We processed the 1-Hz SF GPS data with both VADASE (Variometric Approach for Displacement Analysis Standalone Engine) and RTK positioning approaches. VADASE developed by the Sapienza University utilizes the broadcast orbits and the time differences of the high-rate carrier phase observations to acquire the receiver motions at centimeters accuracy level. The RTKLIB software (Tomoji Takasu) was used for RTK solutions which requires reference stations. The comparisons between VADASE and RTK solutions for all the 1-Hz SF GPS stations are in general consistent. We also compare the VADASE 1-Hz SF GPS solutions with the nearby 40 m away DF GPS stations. The differences between these two are about 3 mm/s and 5 mm/s for H and V component, respectively. Based on the seismological observations, the Meinong event has a strong directivity effect with the seismic waves propagating mainly toward the west to where our GPS stations are located. This effect can be clearly seen in most of the 1-Hz SF GPS solutions indicating 25-40 cm/s, EW-PGV, in contrast to 7-20 cm/s, NS-PGV. Two stations however, show significant large NS-PGV of 32-40 cm/s in comparison with the EW-PGV of 5-11 cm/s. These two stations are located near the E-W-trending Hsinhua fault, where the fault may act as a structural barrier which caused fault-normal motions observed. The use of the VADASE approach in the 1-Hz SF GPS for the 2016 Meinong earthquake clearly demonstrates the feasibility of SF GPS Seismology.

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Early recurrence of an M6 intraplate earthquake (5.8 years) observed in northern Kanto region, Japan, after the 2011 Tohoku-oki earthquake

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The March 2011 Mw9.0 Tohoku-oki earthquake caused significant stress changes in the eastern half of Honshu Island, resulting in the excitation of widespread seismic activity. In northern Kanto region, swarm-like normal faulting activities were induced. One of such events was an M6 event on 19 March 2011 (hereafter called event A).

Approximately 5.8 years later on 28 December 2016, another M6 normal fault earthquake occurred (hereafter called event B). The epicenter of this event determined by the Japan Meteorological Agency is located a few kilometers away from that of the event A.

Performing InSAR processing using Japanese ALOS and ALOS-2 satellite data, it was found that the coseismic displacements for the two events were remarkably similar when the interferograms obtained using data acquired from the same direction were compared. Specifically, the locations of displacement discontinuity lines directing NW-SE, which should correspond to surface rupture, were almost identical, and the displacement patters were also similar, suggesting that the same fault ruptured.

The slightly larger displacement for the event A (maximum displacement discontinuity of ˜45cm compared to ˜30cm for the event B) indicates that this event was associated with larger slip on the fault at least close to the ground. A preliminary inversion for the event B found a dip angle of 42 degrees with fault slip confined in the upper-most 5km in the crust.

Two questions arise from our result: 1) How can only the upper part of the seismogenic layer (within 5km) rupture? 2) How can an M˜6 earthquake re-rupture with such an extremely short time interval of 5.8 years? Two hypotheses can be proposed for the latter question: either a rapid loading of the fault occurred after the event A, possibly associated with the postseismic deformation due to the 2011 Tohoku-oki earthquake, or the stress level on the fault remained high after the event A, enabling further slip on the fault without significant loading.

*J05-5-02
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Crustal deformation process in Mid-Niigata as observed by dense GPS network before and after the 2011 Tohoku-oki earthquake

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The Niigata-Kobe Tectonic Zone (NKTZ) is a deformation zone along the east coast of Japan Sea, with localized E-W contraction (Sagiya et al. 2000). Meneses-Gutierrez and Sagiya (2016) studied strain rate distributions based on GPS data from GEONET in central Japan before and after the Tohoku-oki earthquake and found persistent localized contraction (4-10x10-8/yr), in northern NKTZ, showing that the concentrated contraction is mainly inelastic in the form of aseismic fault slip. However, complete scale characterization of the deformation source was not possible due to limited spatial resolution of the GPS data.
In 2010, the Association for the Development of Earthquake Prediction in collaboration with Nagoya University, constructed 20 continuous GPS sites in Mid-Niigata. Analysis of this network with GEONET allows a better description of the deformation source in the area. We evaluate the Mid-Niigata response during the preseismic (2008-2011) and postseismic period (2013-2016) of the Tohoku-oki earthquake. We calculate horizontal strain rate distributions from the displacement rate data using Shen et al.'s method (1996), with a 15km distance decay constant. Then, we decompose the E-W strain rate with respect to its wavelength following Meneses-Gutierrez and Sagiya (2016). We found persistent localized contraction in the short wavelength component within 40 km before and after the quake. However, differences in the amplitude and horizontal location of the localized deformation suggested that elastic heterogeneities of the crust, acting in different sense before and after the event, might affect the deformation. We modeled the deformation in the preseismic and postseismic period considering an aseismic fault and an elastic heterogeneity as the source of deformation. We found that a fault cutting the whole crust at an angle of 30-40º with a slip rate >10mm/yr and an elastic heterogeneity with horizontal width of 60km located above the fault can explain the deformation.

*J05-5-03
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Crustal deformation in and around the Atotsugawa fault before and after the Tohoku-Oki earthquake

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The 2011 Tohoku-Oki earthquake (Mw9.0) provides us the first opportunity to examine the responses of strain accumulation zones and active faults to megathrust earthquakes with dense permanent GPS network. In this presentation, we report the differences and/or similarities between pre, co, and post seismic crustal deformation of the earthquake using GPS data in and around the Atotsugawa fault, located at the central part of Niigata-Kobe Tectonic Zone (Sagiya et al., 2000).
We used daily coordinates obtained from the GPS stations operated by university group in addition to GEONET. For the pre- and post-seismic period, we estimated the velocity fields by removing annual and semi-annual components. For the co-seismic displacement, we calculated 5 days average of the coordinates before and after the earthquake, respectively, and subtracted each other. From the velocities and displacements, we calculated the strain rates following the method of Shen et al. (1996).
Spatial pattern of the co-seismic strain, which is the elastic response, is completely different from the pre and post seismic strain rates pattern. Therefore we conclude that the pre and post seismic strain concentration, similar to each other, is mainly caused by the inelastic straining (e.g. viscous flow) which is essentially driven by the absolute stress. The absolute stress accumulated over a long time scale is far larger than the stress change by one earthquake, which explains the similarity between pre and post seismic strain rates.
Looking in detail, the sense of pre- and post-seismic strain rates reverse in the south of the Hida mountain range and to the east of Mt. Ontake. Both regions are known as thermally active areas and many small earthquakes have been occurring frequently. Therefore, the change in the strain rates in these regions might be related to the volcanic activities.

*J05-5-04
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The role of the lower crust in crustal deformation of the Japan island arc

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In the Japanese island arc, interplate locking along the subduction interface of the Pacific plate and the Philippine Sea plate has been considered as the main source of the crustal deformation. On the other hand, detailed analysis of crustal deformation before and after the 2011 Tohoku-oki earthquake has revealed existence of persistent deformation associated with the Niigata-Kobe Tectonic Zone, a major inland deformation zone (Meneses-Gutierrez and Sagiya, 2016), which is independent of the mechanical interaction at the subduction interface. This observation suggests that activity of inland deformation zones is driven by regional tectonic stress that has been built up over a geological time scale. In addition, a special structure that promotes localized deformation must exist in the lower crust associated with active deformation in the upper crust. Such an idea is supported by a numerical simulation study, in which shear localization occurs in the lower crust beneath an inland active fault even with a slow fault slip rate such as 1 mm/year. The nonlinear rheology is considered to be the most important cause of the shear localization (Zhang and Sagiya, submitted). Thus it is expected that localized deformation in the lower crust is pertinent to each active fault. Once such a structure is created in the lower crust, it in turn controls the deformation of the upper crust. Such an idea is supported by the fact that crustal deformation pattern around active faults is well explained by an elastic dislocation model with a locking depth of ~15km. Around the Atera fault and the Gofukuji fault, major left-lateral strike slip faults, observations with dense GNSS network show that the lower crustal shear localization beneath the active fault traces continue even during significant perturbation due to the 2011 Tohoku-oki earthquake (e.g. Kumagai et al., 2017). The idea also provides a physical basis for the block modeling of inland areas.

*J05-5-05
Joint Symposium / J05. Crustal dynamics: Multidisciplinary approach to seismogenesis

Importance of fault rheology around brittle-plastic transition in long-term slip rate of major faults

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A ductile shear zone underlies a seismogenic part of a major fault, and its rheology may significantly affect the long-term slip rate. I have conducted numerical simulations of earthquake sequences on a major fault penetrating a crustal plate under a constant far-field stress tau_pl, using a rate- and state-dependent friction-to-flow fault constitutive law. In this law, shear resistance is approximately given by a rate- and state-dependent friction law in a shallow brittle part of the fault, and by power-law creep in a deep fully plastic part. The rate-dependency of the shear resistance takes the maximum value in a transitional regime between them. Note that the peak in the rate-dependency does not necessarily correspond with peak shear resistance. If we assume excess pore pressure at depth which limits the effective normal stress at a certain value, then a Christmas-tree-like strength profile does not exist, but a remarkable peak in the rate-dependency still appears in the transitional regime. In present simulations, the fault hosts repeating earthquakes in the brittle part, and slips by a long-term speed V_pl on average which depends on tau_pl. The relation between tau_pl and V_pl is very well explained by a power law which is similar to what unstable steady-state solutions with uniform slip rates V_ss follow. It should be noted that V_pl is larger than V_ss for the same tau_pl approximately by a factor of 2 due to heterogeneous distribution of shear stress. Since the relation between tau_pl and V_ss is given by spatial average of the rate-dependency, the transitional regime having the prominent peak in the rate-dependency most significantly contributes to the amount of stress perturbation required to change the long-term slip rate of the fault.

*J05-5-06
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Seismicity and Geothermal activities in the Upemba Rift Basin (SE of the DR Congo)

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The Upemba Rift Basin (URB) in the Southeastern area of the DR Congo is one of the nascent southwestern branch of the East African Rift System (EARS). Classically, the EARS had been subdivided in two developed branches : eastern and western branch. But, recent studies and observations led to the definition of two additionnal nascent branches, a Southeastern and a Southwestern.

The first develops in the Mozambic rift channel and the second includes the Okavango basin in Botswana, the Luano, Lukusashi, Lwangwa rift valleys in Zambia and the Mweru and Upemba rifts in DR Congo. Among them, the URB is the less knwon and poorly documented. It is oriented NE-SW and fill by the Karoo and recent glacio-fluvio-lacustrine sediments.

Gravity and structural evidence as long as seismicity and geothermal activities confirm the rifting ascent processus. The surface tracing, poorly controlled by gravity due to the reduced number of measurement points, is transverse to a sub-meridian gravity accident between 26 and 27 East meridians.
Last twenty years seismic events recorded are generally of magnitude Mb about 4.2 showing the seismicity axis parallel to the NE-SW trend of the structural look of the recent rift basins. Major earthquakes focal mechanism solutions are consistent with the NW-SE crustal extension.

Numerous thermal springs had been recognized around the URB and the first, now defunct, geothermal power plant in Africa built in 1953 in the Upemba valley. Its geothermal system is still active (recent exploitation indicates hot spring of about 85.0 ~ 87.2 celcius degree, 60 Tons/hour outflow). A recent Natural Source Audio Magnetotelluric profile below the thermal spring indicates the presence of an high resistivity dyke body (up to 10000 ohm-m2 resistivity). This particular area requires a more scientific investigation.

*J05-P-01
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Investigation of remote earthquake triggering after the 2011 M9.0 Tohoku-oki earthquake

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After the occurrence of the 2011 M9.0 Tohoku-oki earthquake, increased seismicity has been observed over the Japanese Islands due to increased static and/or dynamic stresses (e.g., Toda et al., 2011; Miyazawa, 2011). Miyazawa (2011) showed that a dynamically-triggered earthquake front propagated along Japan following the Tohoku-oki earthquake.

In this study, we investigated the triggering mechanism and remote activation in more detail. We first analyzed Hi-net (NIED) continuous waveform data to identify remote activation in the first minutes after the occurrence of the Tohoku-oki mainshock. We located events that are not listed in the JMA catalogue, with magnitudes from 1.2 to 3.4, which correspond to the arrival of Tohoku-oki surface waves in areas like Aichi, Hyogo and Tokushima prefectures, as well as Kyushu, at about 1350 km from the Tohoku-oki epicenter.

To determine the dominant triggering surface-wave phases, we analysed low-frequency waveform displacements at locations where remote triggering has been observed. The occurrence time for some of the analysed triggered events in Kyushu correlates well with the arrival of large surface-wave displacements on the transverse component, suggesting that the Love-waves, rather than the Rayleigh-waves, may have played the main role in triggered these remote earthquakes. The associated dynamic stresses are large, with values of ~150 kPa in southernmost Kyushu. These observations imply that induced sharing motion may have been responsible for the triggering of some of the detected remote events.

We also looked at the JMA earthquake catalog to observe the duration of increased seismic activity in areas of remote earthquake triggering. We found a clear increase in seismicity that lasted from a few days to about two weeks, depending on the activated area. The geothermal/volcanic areas in Kyushu show the longest and most clear seismicity activation.

*J05-P-02
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Simulation of postseismic deformation caused by the 2011 Tohoku-Oki earthquake

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We are developing a 3-D viscoelastic model using the FEM to understand the postseismic deformation that followed the 2011 Tohoku-Oki earthquake. The question of which elements of the viscoelastic media affect the surface deformation is of particular importance. We first examined the individual effects of two different viscoelastic media, the mantle wedge and the oceanic mantle, which produce almost opposite deformation patterns. The mantle wedge controls eastward motion, uplift of the Pacific coast and offshore regions, and extension across a broad area. In contrast, the oceanic mantle controls dominantly offshore westward motion, subsidence across a broad area, minor uplift of the surrounding areas, and contraction offshore. We then developed four different models to clarify which elements of the viscoelastic media affect the observed surface deformation. The simplest model, with uniform viscosity for all viscoelastic media, could explain the horizontal deformation but not the vertical deformation. The second model, with different viscosities for the mantle wedge and the oceanic mantle, could explain the onshore observations but not those on the seafloor. The third model, which includes a thin weak layer beneath the slab, could essentially explain the near-field onshore and seafloor observations but could not explain the far-field data. The final depth-dependent model was able to explain the far-field data as well as the near-field data. In these typical models, it is of particular importance to consider the different viscosities between the mantle wedge and the oceanic mantle, and to include a thin weak layer beneath the slab. Far-field data as well as near-field data are also important for constraining the viscoelastic structure. Clearly, viscoelastic relaxation alone cannot explain the observed deformation. We are now developing a combined viscoelastic and afterslip model.

*J05-P-03
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Spatiotemporal distribution of locking and aseismic slips prior to the 2011 Tohoku-oki earthquake

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We obtained the horizontal and vertical tectonic crustal deformation in the Tohoku district. We investigated GNSS data for seven years just prior to the 2011 Tohoku-oki earthquake (M9.0). We set the average displacement rate of three GNSS stations in Niigata prefecture as a reference. Chebyshev polynomials enabled high-precision estimation of the tectonic crustal deformation. We determined an optimal order of the polynomials, by minimizing AIC. After correcting offsets caused by coseismic crustal deformation and antenna exchange in the time series, we fitted logarithmic curve to horizontal data to eliminate the effects of postseismic crustal deformations of the following three large earthquakes: the 2003 Tokachi-Oki (M8.0), the 2005 Miyagi-Oki (M7.2), and the 2008 Iwate-Miyagi nairiku earthquakes. Then, we obtained the tectonic crustal deformation, by subtracting common-mode errors and the annual and semi-annual periodic signals from the time series. Then, we performed the inversion analyses for the tectonic crustal deformation with a time interval of one year, and estimated spatiotemporal interplate locking and aseismic slip distributions. We used the geometry model of the Pacific plate by Nakajima and Hasegawa (2006). We employed an inversion analysis which includes the following three prior constraints: the spatial slip distribution is smooth to some extent, slip directions are mostly oriented in the direction of plate convergence, and the temporal change in locking and slip distributions was smooth to some extent (Yoshioka et al., 2015). The results of our inversion analyses revealed locking of approximately 9 cm/year at the offshore of Miyagi prefecture during the period from 2004 to 2010, indicating strong interplate coupling. We also found that locking was 2 cm/year at the middle of offshore Sanriku in 2004, and it became gradually smaller and almost disappeared in 2010.

*J05-P-04
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Source processes of the M6-class repeating earthquakes which occurred in northern Ibaraki Prefecture, Japan, on 2011 and 2016

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An M 6.3 crustal earthquake occurred on December 28, 2016 in northern Ibaraki Prefecture, Japan. Since just after the great 2011 Tohoku Earthquake M 9.0, a significant increase in the shallow normal fault type seismicity has been observed around this area, and the M 6.1 earthquake had occurred on March 19, 2011. The crustal deformations of the 2016 and the 2011 earthquakes, estimated by InSAR data, are almost identical (GSI, 2017), which means that comparable size earthquakes have repeated in the interval of only about 5.7 years. However, the resolution is insufficient to discuss precise source mechanics, so source process inversion analyses using near field strong motion data are performed in this study.
The waveforms of the K-NET and KiK-net (NIED) were used in these inversion analyses. Basically, identical stations were selected for the 2016's and 2011's events. The acceleration waveforms were filtered between 0.03 and 0.8 Hz, and were integrated to velocity waveforms for the inversion analyses. The source processes were inverted by the multi time window method. The size of sub-faults for the inversion analyses were set in 1 km.
The epicenter of the 2016's event is located at about 7 km south of the 2011's event. Though, it was revealed that the rupture of the 2016's event propagated toward the north and its large slip area (asperity) exists fairly near the asperity of the 2011's event. However, the strike and the dip of these events are different and it suggests that the fault planes of the events are not identical. Furthermore, the estimated slip distributions show that the asperities of two events scarcely overlap each other. According to these results, it is deduced that the dominant slip areas of the 2016's and 2011's events are different. The inversion analyses suggest a following conclusion: adjacent but alternate faults had been activated in the interval of about 5.7 years.

*J05-P-05
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Numerical Simulation of Plate Deformation and Stress in the Andaman Subduction Zone

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The oblique subduction of Indo-Australian plate beneath the Eurasian plate in the Sumatra-Andaman region is characterized by the complex deformation patters. In order to investigate surface deformation and stress patterns in the subducting and overriding plate, we have set up a three-dimensional (3D) numerical simulation utilizing 3D density model, derived from the joint modelling of satellite free air anomalies and geoid undulation. The boundary condition for the model is constrained from the plate velocities at the subduction zone and material properties are derived from the seismic velocities and density model. The simulation of stress, strain and velocities, using different rheologies (elastic and viscous) shows a good correlation with the observed GPS velocity components and seismicity of the region.

The 2016 M6.5 Pidie Jaya Earthquake, Aceh Province, Indonesia; Which Fault?

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The 2016 M6.5 Pidie Jaya Earthquake, Aceh Province, Indonesia occur in the morning at 05. 03.36 local time. The epicenter was first automatically estimated by BMKG inland at 5,19 N and 96,36 E, then updated offshore 5,25 N dan 96,24 E, in the depth of 15 Km. The shaking was widely felt across Aceh Province, with intensity VII-VIII MMI, causing 106 casualties, 700 injuries, and 16.238 house damages (BNPB, 2017). This earthquake occurred in place where no fault is mapped in the 2010 National Seismic Hazard Map of Indonesia. The National Center for Earthquake Studies then conducted survey to mapped the source fault of the earthquake. We conducted field observation of surface ruptures and deploy temporary continuous GPS measurement 3 days after the main shock. We analyze the fault location based on field observation data, seismicity data, geomorphology data, and geodetic INSAR data. We present the preliminary result of the fault source of the 2016 Pidie Jaya earthquake based on those data, which is updated in the New National Seismic Hazard Map 2016.

*J05-P-07
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Regional stress field inferred from focal mechanisms obtained by dense seismic observation in the northern South Island, New Zealand

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The northern South Island and the southernmost North Island of New Zealand lie in the transitional area of subduction of the Pacific plate, with the Pacific plate subducting beneath the Australian plate obliquely from the northeast. Due to the plate subduction, active seismicity in the northern South Island can be seen. For example, a Mw 7.8 earthquake occurred in the Kaikoura region of northern South Island at 11:32 am (UT) on 14 November 2016. In this study, we obtained focal mechanisms of the micro- to moderate-sized earthquakes in order to estimate the spatiotemporal variation of the crustal stress field, including the Kaikoura earthquake.
We analyzed the data acquired by a dense seismic array (see also Okada et al, this meeting) which has been recording over 2 years from 1 April 2013 to April 2015. We determined focal mechanisms using the HASH program (Hardebeck, 2002; 2003). During that time period, there have been two major seismic clusters; the first, consisting of aftershocks of the 1990 Lake Tennyson earthquake, occurred in the center of the northern South Island, while the second, which consisted of aftershocks of the 2013 Cook Strait earthquakes, occurred in the northeast of the northern South Island. For shallow earthquakes, strike-slip type focal mechanisms seem to dominate. P axes were oriented to ~N120E, which is similar to that found in previous studies (Reyners et al., 1997; Balfour et al., 2005; Sibson and Ghisetti, 2011; Townend et al., 2012) and which seems to be consistent with most of GEONET-CMTs of the aftershocks of the 2016 Kaikoura earthquake. T axis were oriented to NE-SW. For intermediate-deep earthquake, normal, strike-slip, reverse faulting seems to be mixed. Most of the P axes were oriented to NE-SW, which is also consistent with previous studies (Reyners et al., 1997; Townend et al., 2012).

*J05-P-08
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Crustal stress and strain inversion of the Taiwan orogen using a mixed linear-nonlinear Bayesian approach

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The state of stress and strain in the crust is fundamental information for understanding bonging tectonic status and processes. It is common to use seismic data for inverting stress state at depths and geodetic data for estimating strain rates on the surface. However, it is arbitrary to determine spatial smoothing in regular damped least-squares for stress and strain inversions. Therefore, we extend the common stress and strain inversions into a mixed linear-nonlinear Bayesian framework, which provides objective way to estimate regularization parameters. In this method, one can estimate principal stress orientations with 3D smoothing by using focal mechanism solutions. The smoothing and fault plane selections can be determined by the Markov Chain Monte Carlo (MCMC) approach with the Metropolis algorithm. We show examples of stress and strain inversions for the Taiwan orogen and demonstrate how crustal stress changes after a large seismic event. The results show that the stress state of Taiwan is mainly dominated by strike-slip and reverse faulting with normal faulting in the northern and northeastern Taiwan, which is consistent with other studies. The stress state changes after the 1999 Chi-Chi earthquake is consistent with postseismic movement.

*J05-P-09
Joint Symposium / J05. Crustal dynamics: Multidisciplinary approach to seismogenesis

Afterslip and viscoelastic components observed in surface gravity change after the 2011 Great Tohoku earthquake

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The 2011 earthquake off the Pacific coast of Tohoku imposed significant stress change within the crust and mantle, which results in postseismic crustal deformation and gravity change. In this presentation, we show gravity change on the ground of Tohoku, Hokkaido and Kanto areas during the period between May 2011 and July 2016.
The gravity changes measured with an FG5 absolute gravimeter showed rather monotonous decrease of 30-40 microgals during 2011-2014. Since the elevation changes in the same period are 10 to 20 cm, the gravity decrease can be well explained in terms of afterslip around the fault of the Tohoku earthquake. Surprisingly, however, the gravity trend showed slow but steady increase of 10 microgals since 2014 although the uplifting is still going on in the same period.
Remembering that the gravity change is composed of contributions from elevation change and volumetric strain change (density change), the gravity increase since 2014 is likely to reflect viscoelastic strain change within the mantle. The result will be discussed in more detail based on viscoelastic modeling of a spherical earth.

*J05-P-10
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The spatial distribution of the stress ratio in the aftershock area of the 2000 Western Tottori Earthquake

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A statistical approach to estimate a spatial stress pattern from P-wave first motions has been developed. In this approach, without the determination of focal mechanisms, the spatial pattern of stress tensor is evaluated under the two assumptions: (i) the orientation of a fault plane is distributed randomly and uniformly; and (ii) the slip orientation of faulting is parallel to the one in which the shear stress is maximized. With the two assumptions and smoothness constraint on the spatial variation in the stress tensor, the best estimate of the spatial stress pattern to fit observed P-wave first motions is found in the framework of a Bayesian statistics.

This approach was applied to the dataset of P-wave first motions taken from the aftershocks of the 2000 Western Tottori Earthquake. From the dataset compiled by Kawanishi et al. [2009, JGR], the P-wave first motions with which O-C time for the P-wave arrival is within 0.1 s and that for the S-wave arrival is within 0.2 s (if the S-wave arrival is picked) were selected. After this selection, 47,570 P-wave first motions for 3592 events were remained and analyzed.

From the estimated stress tensor, the spatial pattern of the stress ratio R = (sigma_1-sigma_2)/(sigma_1-sigma_3) was calculated where sigma_1, sigma_2, and sigma_3 denote the maximum, intermediate, and minimum principal stress, respectively. In the southern part of the main fault orientated NNW-SSE, the value of R along the western side of the fault is high while it is low along the eastern side. The Tottori earthquake has a left-lateral strike slip fault, and therefore we may assume the stress field after the mainshock is compressive and extensional along the western and eastern sides along the southern part of the main fault, respectively. The spatial pattern of the stress ratio revealed in this study is consistent with the assumed stress field.

Seismic velocity structure in the lower crust beneath the seismic belt in the San-in district, Japan

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In the San-in district in southwest Japan, a linear distribution of epicenters is seen along the Japan Sea coast. The linear distribution is called the seismic belt in the San-in district. Large earthquakes also occurred in the seismic belt. What localizes the earthquakes in the San-in district far from the plate boundary? We thought that the model proposed by Iio et al. (2002, 2004) could answer the question. The model is as follows. A part of the lower crust has low viscosity. The low viscous part is called 'weak zone'. The stress and strain in the upper crust are concentrated right above the weak zone, and earthquakes occur there. To verify whether the weak zone exists in the lower crust beneath the seismic belt, we estimated the seismic velocity structure there by seismic travel time tomography.
We carried out the tomography with the program, FMTOMO (Rawlinson et al., 2006). FMTOMO implements wavefront tracking, which can trace rays robustly. The area of the velocity model contains San-in, Sanyo, Shikoku and a part of Kinki district. The depth of the model extends 0-81 km. We used travel times picked by Japan Meteorological Agency (JMA) for earthquakes that occurred in the study area. In addition, we used the travel times manually picked for earthquakes that occurred within the Philippine Sea Slab, because seismic waves from the earthquakes to stations in the San-in district pass through the lower crust beneath the San-in district. We expect that the data can improve the resolution in the lower crust.
The tomography revealed that the lower crust beneath the seismic belt has low velocity anomalies and might have low viscosity, since velocities of rocks decrease with temperature and/or water content. Therefore, the results of this study support the model proposed by Iio et al. (2002, 2004).
Acknowledgement: We used JMA's earthquake catalogs. We also used waveform data from permanent stations of National Research Institute for Earth Science and Disaster Resilience.

*J05-P-12
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Depth dependence of stress field investigated from microseismicity in northwestern Kii Peninsula, southwestern Japan

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The heterogeneous structure of the upper crust is one of the important factors controlling the earthquake occurrence. Therefore, understanding the influence of the heterogeneous structure of the upper crust on seismic activity leads to elucidating the process of the inland earthquake occurrence. To understand the above, we investigated the relationship between seismic activity and heterogeneous structure accommodating faults and fluids. In order to investigate the relationship between heterogeneous structure and seismic activity, the best study area is a region with high seismic activity. Thus, we selected the northwestern Kii Peninsula as the study area because of its high seismicity.
In this study, we focused on the seismic activity of the upper crust, and we investigated focal mechanism solutions of the microearthquakes and stress field in detail.
The focal mechanisms determined in this study are categorized into three groups and the predominant depths for the respective groups are different: 1) N-S tensional normal-fault type events mainly occur in the shallower part, 2) E-W compressional reverse-fault type at middle depths, and 3) N-S tensional and E-W compressional strike-slip-fault type in the deeper part. We carried out stress tensor inversions and the results also indicate that the stress field varies with depth: the shallower part is characterized by the strike-slip-fault type stress field of with N-S tension and E-W compression while the deeper part is the reverse-fault type with E-W compression.
The complicated distributions of focal mechanisms and stress mentioned above can be explained by thermal stress caused by a heat source in the lower crust and vertical weak planes related to the geological structure.

*J05-P-13
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Tectonic Loading of the Atera Fault inferred from Dense GNSS Observation

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he Atera Fault is in the east of Gifu Prefecture is a major active fault in Japan. The fault is left-lateral strike slip in the NW-SE direction, consistent with E-W compressional stress. The geological slip rate is 2~4mm/year. However, a hydraulic fracturing experiment and the GEONET F3 solution suggested the Atera Fault undergoes right-lateral displacement (Yamashita et al. 2010). We study crustal deformation and stress filed of the Atera Fault by GNSS observation and numerical modeling. We install dense GNSS network near the fault trace with an average interval of several kilometers in order to reveal detailed crustal deformation pattern. Based on GNSS daily coordinate from is January 2014 to October 2016, we calculate average horizontal velocity at each GNSS site. The velocity pattern is dominated by the postseismic deformation of the 2011 Tohoku-oki earthquake and interplate coupling at the Nankai Trough. We correct overall deformation pattern in order to extract displacements related the fault activity. After the correction, a left-lateral displacement pattern is identified. Comparison with the elastic dislocation model showed that our observation is consistent with geological estimated fault slip rate (2~4mm/year) and the seismologic layer thickness (~15km). We also evaluate the topographic perturbation on the crustal stress filed under a lithostatic equilibrium. The calculation suggests that the topographic effect is significant at shallow depth (~5km) and greatly affects the crustal stress pattern. The calculated maximum compressional axis at the hydraulic fracturing site depth of 350m is in the N-S with a differential stress of 2~4 MPa. The results demonstrate that the motion of the Atera Fault is left-lateral, consistent with the regional stress filed. It is also suggested that tectonic loading of a crustal fault does not change even under elastic perturbation due to postseismic deformation and interplate coupling.

Spatio-temporal variation in Coda Q in the northeastern part of Niigata-Kobe Tectonic Zone in 2009-2014

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We focus on a high strain rate zone called Niigata-Kobe Tectonic Zone (NKTZ) (Sagiya et al., 2000) to understand a stress accumulation process in seismogenic zone. Jin and Aki (2005) showed that low coda Q at low frequency bands corresponded spatially to the high strain rate zone. Hiramatsu et al. (2013) and Tsuji et al. (2014) suggested that the cause of the high strain rate zone was attributed to the high deformation rate below the brittle-ductile transition zone in the crust in the central part of the NKTZ. This study investigates details of the spatial distribution of coda Q in the northeastern part of the NKTZ. We have analyzed 646 events from January 2009 to February 2011 (period I) and 2194 events from January 2012 to October 2014 (period II).
We compare the data between the periods I and II. We applied t tests to analyze these temporal variations and recognize that the variations are not statistically significant. These facts imply that the temporal variation in coda Q caused by the 2011 earthquake is not significant in this study area.
The spatial distributions of coda Q at the 2-4 and 4-8 Hz frequency bands for periods I and II are found to be negatively correlated with the differential strain rate (Sagiya et al., 2000; Nishimura 2015, personal communication). Positive correlations are found between the perturbation of the S-wave velocity (Nakajima and Hasegawa, 2007) at 25 km depth and coda Q at the low frequency bands, and between the perturbation of the S-wave velocity at 10 km depth and coda Q at the middle frequency bands for both the periods in this study area. These facts imply that the spatial distributions of coda Q at the low and middle frequency bands reflect mainly the heterogeneity of the lower crust and the upper crust, respectively. We suggest that the deformation in the upper crust, as well as the ductile deformation in the lower crust, may be a dominant cause of the high strain rate in the northeastern part of the NKTZ.

*J05-P-15
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The gravity anomalies analysis over the active reverse fault zones in Japan

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Our object is to examine subsurface features of the reverse fault zones and defines their faulting type, dipping direction, continuity and segmentation through gravity anomalies .In this study, we analyze 43 reverse fault zones in northeast Japan and the northern part of southwest Japan among major active fault zones selected by Headquarters for Earthquake Research Promotion.
We compiled the gravity data published by the Gravity Research Group in Southwest Japan (2001), the Geographical Survey Institute (2006), Yamamoto et al. (2011), Honda et al. (2012), and the Geological Survey of Japan, AIST (2013) in this study. We apply terrain corrections with 10 m DEM (Sawada et al. 2015) under the assumed density of 2670 kg/m3 and a band-pass filtering, then remove linear trend. We calculate the derivatives and structural parameters from a gravity gradient tensor, such as a first horizontal derivatives (HD), a first vertical derivatives (VD), a normalized total horizontal derivative (TDX), a dip angle (β), and a dimensionality index (Di),
At 21 fault zones, the subsurface structural boundaries are highlighted clearly along the faults with the derivatives. The structural boundaries are partly detected at 13 fault zones and not detected at 9 fault zones. At these 9 fault zones, gravity anomalies do not highlight the fault structures but they show low anomaly basins, which restrict surface traces of the active fault zones.
We divide the results into several groups according to their faulting types, such as reverse faults, reactivated reverse faults in which a reverse fault structure is dominant, reactivated reverse faults in which a normal fault structure is still dominant, and normal faults with gravity anomalies of a trough structure.
The Nagano basin east margin fault zone is newly formed reverse faults in the sedimentary basin in the Quaternary. However, gravity anomalies detect a normal faulting. We suggest that gravity anomalies detect the east margin of the trough.

*J05-P-16
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Influence of water on rheological properties of feldspar aggregates under the lower crustal temperature and pressure

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Fluids in deep part of the crust have an important role in deformation and seismicity of the crust. However, experimental data of crustal materials under the lower crustal conditions are insufficient. In this study, we performed high temperature and high pressure deformation experiments to reveal rheological properties of feldspars under hydrous conditions. Axial compression tests on synthetic polycrystalline anorthite with 0.5 wt% of water were performed in a Griggs-type solid medium apparatus at temperature of 900 deg C and various confining pressures of 0.8-1.4 GPa. Times were changed to investigate the reduction of strength by volume and grain boundary diffusion of water into samples. Water contents in samples were measured by an FTIR method. As a result, strengths of wet anorthite tended to decrease with increasing time or strain magnitude. It was suggested that anorthite samples were still not saturated with water in time range of this study. Strengths of wet anorthite also decreased with increasing confining pressures. Differential stresses were significantly lower than predicted values by previous flow laws for wet anorthite obtained by low pressure experiments (<0.5 GPa). This implies that the effect of fugacity of water on strength in higher pressure might be larger than those predicted by lower pressure experiments. Our experiments show that the strength of hydrous regions in the lower crust becomes lower than that predicted by previous studies.

*J06-1-01
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Numerical experiments on estimation of frictional properties and slip evolution on the Bungo Channel Long-term SSE fault with Ensemble Kalman Filter

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Long-term Slow Slip Events (LSSEs) occur on the plate interface beneath the source regions of the interplate large earthquakes. The activity of SSEs possibly changes before large interplate earthquakes and SSEs may directly trigger them. Our final goal is to estimate slip evolution and frictional parameters with Ensemble Kalman Filter (EnKF), one of data assimilation methods. In this paper, we execute numerical experiments for the Bungo Channel LSSEs, southwest Japan, before analyzing the actual GNSS observation data.
Our previous experiments for the Yaeyama SSEs in the Ryukyu region showed that, for well recovery of parameters and slip evolution with EnKF, the conditions are: 1)SSEs have been observed more than once, 2)The duration of SSEs is long, 3)SSEs are observed at observation points with enough density and coverage. Hence, we target at the Bungo Channel LSSEs which have occurred several times with the duration of about 1 year.
We set a dipping fault in a homogeneous elastic half space and assume a rate-state friction law and the slowness law of state evolution. We set a circular velocity-weakening patch (radius R=40km) on the fault plane with frictional parameters so that R/Rc=0.9 (Rc: critical nucleation radius). We generate synthetic observed data by adding random numbers to the simulated surface displacement rates and performed EnKF estimations of the frictional parameters A and L on the fault plane and B-A on the patch along with the slip rates and the state variables.
The results show that if the duration of SSEs is sufficiently longer than the assimilation step, update is moderately performed and calculation does not stop. As long as we use a simple model, we can estimate the frictional parameters on the fault with considerable accuracy for the actual GNSS (GEONET) distribution.
In our current model, frictional parameters are uniform on the SSE patch. We need to perform numerical experiments with more complicated models.

*J06-1-02
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Long-term slow slip events in the Tokai region, central Japan, before 2000

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The Tokai region, central Japan, has been subjected to many large earthquakes due to the interplate coupling. In order to monitor the crustal deformation in the interseismic period, many kinds of geodetic observations have been conducted. The dense GNSS observation network, named GEONET in Japan since the mid-1990s maintained by Geospatial Information Authority of Japan (GSI), revealed two long-term slow slip events (LSSEs) in the region; one was from mid-2000 to mid-2005 (e.g. Suito and Ozawa, 2009), and the other was from early 2013 and seems to be still ongoing (Ozawa et al., 2016). Ozawa et al. (2016) mentioned that the center of the the ongoing event is near Lake Hamana, which is the south of the center of the 2000-2005 event, and the released seismic moment of the ongoing event will be smaller than the size of the 2000-2005 event. Their result suggests that the LSSEs in the Tokai region are repeating phenomena with variation in size and occurring place.
In order to reinforce the suggestion, I analyzed leveling data from 1981 to 1999 and length change data between 1974 and 1992, which were also obtained by GSI . The network adjusted leveling data show fluctuation in the vertical displacement rate at the inland benchmarks with respect to the benchmark at Omaezaki cape, the nearest site from the trench and show that at least two LSSEs around 1987-1990 and 1983. Compared with 2000-2005 event, the 1987-1989 event is smaller and the 1983 event is the smallest. The 1987-1990 event shows clearer difference in vertical the displacement pattern with respect to that of the 2000-2005 event. It support the possibility of the variation in the occurring place. Although a simple forward modeling using rectangular source fault for the 1987-1990 event show that the amount of released seismic moment was about Mw 6.6, which was smaller than the 2000-2005 event done, the model cannot explain the difference in displacement pattern and more sophisticated model is required.

*J06-1-03
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Correlation between Coulomb Stress Rate Change Imparted by Two Slow Slip Events and Seismic Rate Change in Lower Cook Inlet of the Alaska-Aleutian Subduction Zone

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We identified two long-term slow slip events (SSEs) in Lower Cook Inlet, southcentral Alaska (1995.0-2004.8 and 2009.85-2011.81) by inverting the GPS site velocities (Li et al. 2016). The earlier SSE (SSE1) lasted at least 9 years with Mw˜7.8 and an average slip rate of ˜82 mm/yr. The latter SSE (SSE2) had almost the same area as the earlier one, which is within 40-60 km depth range, and a duration of ˜2 years with Mw˜7.2 and an average slip rate of ˜91 mm/yr.
In order to see whether SSEs can trigger earthquakes outside the slow slipping area significantly and contribute to the early earthquake warning, we resolved the Coulomb stress rate changes on receiver faults in the crust and the slab using two different potential definitions for them. Our results showed that the significantly higher stress rate during SSE1 caused a significant decrease in the seismicity rate after SSE1 ended. However the area in the slab that experienced significant increasing stress rate change due to SSE1 slip did not show a clear pattern of decreasing seismic rate after SSE1 ends. No significant increasing stress rate change area influenced by SSE2 was identified in the crust. The area that experienced a significant increase in stress rate in the slab due to SSE2 slip had a seismicity rate increase right after the SSE2 started and seismic rate decrease after the SSE2 ended.
We also modeled the seismicity in potential triggering areas by using the rate/state stress transfer model (Dieterich, 1994). The observed seismicity can be well fitted with the increase in stress rate of the SSE1 period comparing with the one in the post-SSE1 period. But the stress rate due to slip from SSE2 was not large enough to explain the cumulative seismicity through time. Explaining the post-SSE2 seismicity rate change requires some additional stress rate change such as an increasing slab pull stress rate after the SSE started instead of a uniform slab pull stress rate over all time periods.

*J06-1-04
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Insights into the Causal Relationship between Slow Slip Events and Tectonic Tremors in Guerrero, Mexico

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Similar to other subduction zones, tectonic tremors (TT) and slow slip events (SSE) take place along the deep segment of the plate interface in Guerrero. However, their interaction in this region is not as clear as the Episodic Tremor and Slip observed in Cascadia and Japan. In this study we provide insights into such interaction analyzing the evolution of the deformation fields induced by the long-term 2006 SSE together with independent new locations of TTs and low-frequency earthquakes (LFE). Unlike previous studies we find that the SSE slip rate is the parameter that modulates the TT and LFE occurrence rate in the whole tremor region. This means that the causal relationship between the SSE and the TT activity directly depends on the stressing rate history of the locked asperities that is modulated by the SSE slip rate. We have estimated that the frictional strength of the asperities radiating tremor downdip in the Sweet Spot is around 32 kPa, which is ~2.2 times smaller than the corresponding value updip in the Transient Zone, partly explaining the overwhelming tremor activity of the Sweet Spot despite that the slow slip there is almost three times smaller. Based on the LFEs occurrence rate history during the inter-SSE period we determined that the short-term SSEs in Guerrero take place further downdip (about 35 km) than previously estimated, with maximum slip of about 8 mm overlapping the Sweet Spot. This new model features a continuum of slow slip extending across the entire tremor region of Guerrero.

*J06-1-05
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

EFFECTS OF THE GEOMETRY OF THE MEXICAN SUBDUCTION ZONE TECTONIC-INTERFACE ON THE STRESS TRANSFER DUE TO INTERPLATE SLIP EVENTS.

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We analyze in this work the effects of the tectonic interface geometry of the Mexican subduction zone on the coulomb stress transfer produced by large interplate earthquakes and slow slip events, using a 3D subducting slab model and explicit slip distributions. The interface geometry used here was previously obtained based on seismicity depth profiles along the subduction zone. As a reference for the assessments, we first obtained the stress change over extended fault planes; for slow slip events we considered three plane segments with different dip angles and for earthquakes (M<8.0) we used a single extended fault plane. Next we computed the stress transfer for the same slip distributions along the 3D interface. In all cases the interface surface was discretized by 2.0Km x 2.0Km segments, setting the observing points along the same surface in a staggered-type grid, avoiding in this way possible singularities. Stress tensor changes were computed for a 3D half-space, and analyzed using the Coulomb Failure Stress criterion. The stress changes due to each subfault from each earthquake were computed on each grid segment of the interface and resolved along its specific normal and slip directions. This computation procedure implied that for a given earthquake, or slow slip event with a specific slip distribution, the coulomb stress change distribution could vary depending on its relative location along the surface. Results are presented and compared for the plane segments and the 3D tectonic interface. The stress changes inside the main rupture patches showed relative small variations between both assumptions; however, relatively larger variations could be found outside the main patches, especially where the interface presented bendings along the strike or dip directions. Results suggest that the assumption of planar tectonic surfaces should be carefully explored for this kind of analyses in this region

*J06-1-06
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Laboratory observations of slow stick slip: implications for slow earthquakes and the spectrum of fault slip behavior

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Seismic and geodetic observations show that fault slip occurs via a spectrum of behaviors that include slow earthquakes and tectonic tremor. These phenomena have been observed in a variety of tectonic environments worldwide, however the underlying processes are poorly understood. Here we show results from lab experiments on simulated fault gouge. We used the double direct shear configuration and varied the loading system stiffness (k) to produce the full spectrum of stick-slip behaviors, with durations ranging from 10-3 to 1 second. We measured frictional rheology and elastic wave properties throughout the stick-slip cycle for slow and fast events. At the end of the experiments we also collected the resulting fault zone microstructure. When the loading stiffness is greater than the fault zone critical rheologic stiffness (kc) we observe stable frictional sliding. For k≈kc we document emergent slow-slip events from steady shear. When kc>k we observe audible stick-slip. Stick slip stress drop and event duration vary systematically as a function of the ratio k/kc. For both slow- and fast- slip events, P-wave velocity (Vp) begins to decrease prior to the stress drop and the maximum slip velocity during failure coincides with the largest drop in Vp. Microstructural observations show that with accumulated strain, deformation localizes along sharp shear planes consisting of nanometric grains, which favor the development of frictional instabilities. Once this fabric is established, fault fabric does not change significantly with slip velocity, and fault slip behaviour is mainly controlled by the interplay between fault rheological properties and the stiffness of the loading system. As applied to tectonic faults, our results suggest that a single fault segment can experience a spectrum of fault slip behaviour depending on the evolution of fault rock frictional properties and elastic conditions of the loading system.

*J06-2-01
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Completing the Seismic Cycle: Approaching 100% slip recovery along the subduction megathrust beneath Nicoya Peninsula, Costa Rica

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The seismogenic megathrust beneath the Nicoya Peninsula exhibits magnitude 7.5+ earthquakes approximately every 50 years directly under land. Because of this, there have been numerous geophysical studies there including the Nicoya Seismic Cycle Observatory (NSCO) consisting of dense seismic and GPS networks cooperatively operated by UC Santa Cruz, Georgia Tech, U. South Florida, and OVSICORI. As detailed by a recent high-resolution 3D slab interface model by Kyriakopoulos et al. [JGR, 2015], the megathrust environment below Nicoya has strong along-strike transitions in oceanic crust origin and geometries, including massive subducted seamounts, and a substantial crustal suture. Using GPS data collected from campaign and continuous sites over the past two decades numerous studies have imaged components of the seismic cycle, including late-interseismic coupling, frequent slow-slip events, coseismic rupture of a moment magnitude 7.6 earthquake in 2012, and now several years of postseismic response. We report on a reanalysis of all slip behavior measured through this time, using the 3D geometry and consistent inversion methods to reveal a unified analysis of the full continuum of slip. We find that the late-interseismic locking that was observed in the decade prior to the major earthquake, accurately reflects the combination of episodic slow slip (contributing to weak to low-coupling zones), major coseismic rupture (contributing dominantly to the strongly locked patch), and afterslip (contributing to a combination of strongly locked zone transitioning to intermediately weak behavior). After accounting for all slip observed, little energy is left for significant earthquake behavior, suggesting that the fault has indeed released nearly its full potential, and likewise adding additional credence to the hypothesis that the megathrust environment is weak. Without the long-term and continuous geodetic observations made by the NSCO, this work would not have been possible.

*J06-2-02
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Anomalous gravity changes observed during long-term slow slip events and a possible interpretation based on fluid flow

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Slow-slip events (SSEs) have been observed in many plate boundary zones along the circum-Pacific seismic belt. Previous studies have revealed that high-pressure fluids supplied from the subducted oceanic plate can generate SSEs. However, the behavior of these fluids during an SSE has not been fully elucidated. In this presentation, we discuss a possibility of fluid migrations along the plate interface on the basis of spatiotemporal gravity changes observed by absolute and superconducting gravimeters during recent long-term SSEs in Japan, including those in the Tokai district, the Bungo Channel, and the Yaeyama Islands. The limited spatiotemporal resolutions of the gravity data and uncertainties due to hydrological disturbances preclude us from attributing the gravity changes to the SSEs uniquely. However, after removing the apparent effects due to vertical deformation of the observation sites, there still remain anomalous gravity changes with the order of 1 microGal (10^-8 ms^-2) over the periods of the SSEs. A simple fluid flow model through a fault fracture zone employing Darcy's law predicts gravity variation of 1 microGal/year for a change of 0.6 MPa (=0.1% of the lithostatic minus hydrostatic fluid pressure at a depth of 30 km) and a permeability value of 2 x 10^-11 m^2. The latter is a lower limit for which the rupture becomes slow, obtained by a numerical simulation based on a poroelasticity theory (Yamashita, 2013). These results indicate that the observed anomalous gravity changes can be associated with fluid pressure variations in the slow slip areas. We will continue gravity observations, which is needed to exclude possibilities that hydrological disturbances coincidentally cause these anomalies.

*J06-2-03
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl ip to earthquake)

Meaning and prospect for science of slow earthquakes

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Slow earthquake is a general term for low-speed fault slip phenomena compared to ordinary earthquake. Slow earthquakes with wide range of characteristic times have been discovered since around the end of the 20th century by densely distributed seismic and GNSS observation networks in Japan then detected in many subduction zones along the circum-Pacific. During the last two decades we have recognized that the slow earthquakes were not special events at each region but common phenomena. Deep low frequency tremor and short-term slow slip event (SSE) were independently discovered at Nankai and Cascadia subduction zones, respectively, after that the coupling phenomena of episodic tremor and slip (ETS) were detected in both regions. Deep very-low frequency (VLF) earthquake associated with ETS was firstly detected in Nankai, after a while also detected in Cascadia. Based on recent marine temporal observation at the western Nankai trough region, shallow tremor has been discovered in association with already-known shallow VLF event like as deep ETS. Therefore, one of our next research targets is to find shallow SSE which is expected to host shallow tremor and VLF. Detailed comparison between shallow and deep slow earthquakes will bring new geological and physical constraints for the similar frictional property at the different thermal and pressure regimes. In future, understanding activity mode, environment, and mechanism of slow earthquakes will contribute to development of Earth science in the following three viewpoints. One is to reconstruct the new comparative subductology based on quantitative comparison study of slow earthquakes at different subduction zones. Second is to reconstruct the approach of earthquake science based on a unified understanding of slow deformations and fast slips. Third is to contribute to advanced evaluation for the occurrence of megathrust earthquake based on understanding mutual interaction between slow and huge earthquakes.

*J06-2-04
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Emergence and disappearance of interplate repeating earthquakes after the 2011 Tohoku-oki earthquake: transition between slow slip and earthquakes

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We investigated spatio-temporal changes in the interplate seismic activity following the 2011 Tohoku-oki earthquake (M9.0) in the region where large postseismic slip was observed. We selected interplate earthquakes by their focal mechanisms and conducted hypocenter relocation to examine the detailed spatiotemporal distribution of interplate earthquakes. The results show that many interplate earthquakes, including M˜6 events, emerged immediately after the Tohoku-oki earthquake in areas where weak interplate locking and very few interplate earthquakes had been observed before the Tohoku-oki earthquke. The emergent earthquakes include repeating sequences, and the extremely long quiescence of small to moderate earthquakes before the Tohoku-oki earthquake suggests that the source areas for the post-M9 M˜6 events slipped aseismically during the quiescence. The repeaters' magnitudes decayed over time following the Tohoku-oki earthquake and some sequences disappeared within a year. The emergence of interplate earthquakes suggests that regions where aseismic slip had been dominant, started to cause seismic slip and the disappearance suggest the regions became aseismic again. Such behaviors can be interpreted by conditional stability of faults that show instability when the fault loading rate inclease. We consider coseismic increase of loading rate and subsequent decrease by the afterslip of the Tohoku-oki earthquake caused the aseismic-seismic-aseismic transitions. This indicates that the conditaional stability play an important role in the spatio-temporal distribution of earthquakes in interplate seismogenic zones.

*J06-2-05
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Spatio-temporal distribution of earthquakes around the subducted seamount off Ibaraki in response to the largest Mw7.8 aftershock of the 2011 Tohoku-oki earthquake

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M7 class earthquakes have repeatedly occurred ~100 km offshore of the Ibaraki prefecture at fairly constant time interval of 20 years. It has been revealed that there exists a subducted seamount up-dip of the source region of such repeating M7 earthquakes (Mochizuki et al., 2008). The region coincides with the southern limit of the fault region of the 2011 Tohoku-oki earthquake, where its largest aftershock with Mw7.8 occurred 30 minutes after the main shock.

We collected one-year long seismic data using 31 ocean bottom seismometers around the subduction front of the subducted seamount at a spatial interval of ~6 km from October, 2010, through September, 2011. In the middle of the observation period, the 2011 Tohoku-oki earthquake and its largest aftershock occurred. The epicenter of the largest after shock is located only ~30 km to the west (donw-dip) of the array, and its rupture propagated up-dip toward the seamount. Recent studies on its rupture propagation (Honda et al., 2013; Kubo et al., 2013) revealed that the rupture stopped before the subducted seamount so that its rupture occupies the area in subduction front of the seamount.

More than 20000 earthquakes around the OBS array were recorded. Visual identification and manual picking of P and S arrivals through the records of ~30 stations are unrealistic. Therefore, we applied an automatic picking method that we developed by referring to Grigoli et al. (2014). Having 3-D seismic velocity structure around the region compiled by referring to the existing seismic profiles, we successfully determined the hypocenter of each event by finding a grid point with the maximum semblance value in the model volume.

The resulted distribution of the earthquakes shows two primary layers of seismicity. The upper layer may represent distribution of small scale faults above the seamount. We found seismically quiet region in front of the subducted seamount that appears consistent with the rupture area of the largest aftershock.

*J06-2-06
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Seismic quiescence of deep very low frequency earthquakes from later 2014 in western Shikoku, Japan

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Deep very low frequency earthquakes (VLFEs) are frequently associated with episodic tremor and slip (ETS) at the downdip region of the megathrust seismogenic zone along the subducting plate interface (Ito et al., 2007; 2009). As a member of slow earthquake family associated with slow slip, VLFE activity is expected to be a proxy of interplate slipping. However, the time change of the deep VLFE seismicity has not been investigated well compared to deep low frequency tremor (e.g., Obara et al., 2010). In this study, we investigated long-term changes of the activity of deep VLFEs in western Shikoku where ETS and long-term slow slip event (SSE) frequently occurred.

We used continuous seismograms of 13 F-net broadband seismometers operated by National Research Institute for Earth Science and Disaster Resilience (NIED) from 2nd April 2004 to 29th September 2016. After applying the band-pass filter with a frequency range of 0.02—0.05 Hz, we adopted the matched-filter technique (Shelly et al., 2007) in detecting VLFEs. The synthetic waveforms calculated by the wavenumber integration method (Takeo, 1987) with the fault mechanisms obtained by Ide and Yabe (2014) at multiple grid points in the Bungo channel and its neighboring inland region are used for templates. We defined the detection threshold as eight times as large as the median absolute deviation (MAD) of the distribution.

We detected 700—1000 VLFEs at each grid point for 12 years. In inland region, the cumulative number of detected VLFEs increases steeply every half a year. This stepwise change is caused by ETS. In the Bungo channel, the cumulative number of detected VLFEs increases gradually in 2010 and 2014 influenced by long-term SSEs. Interestingly, the activity of deep VLFEs has been low since the latter half of the year 2014 in this region. The long-term SSEs in 2014 may influence the seismic quiescence of VLFEs.

*J06-3-01
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Rapid Tremor Migration Induced by Pore Pressure Waves

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Observations in different subduction zones suggest that overpressured fluids close to the plate interface may be linked to the origin of tectonic tremors (TT) and low frequency earthquakes (LFE). Fluids at nearly lithostatic pressures within the top few kilometers of the oceanic crust have been inferred in several subduction zones, including the state of Guerrero, Mexico. The actual effect of fluid diffusion on fault zones may strongly affect the seismicity rate by inducing transient changes in the effective fault-normal stresses. These changes propagate slowly (i.e., ~50 meters per day or 0.002 km/h) during fluid-injection tests in the upper crust. However, when fluids are subject to nearly lithostatic pressures at depth (i.e., ~40 km), small pore pressure gradients may induce large transient variations of the permeability that, under some conditions, produce solitary pressure waves propagating much faster across the fault zone. Recent TT epicentral locations in Guerrero using the Tremor Energy and Polarization (TREP) method (Cruz-Atienza et al., JGR, 2015) show that sources of these events migrate with speeds ranging between 10 and 80 km/h during slow slip events (SSE). Migration directions change with time, so they are first parallel to the slow slip front as observed in other subduction zones. However, latter migration directions are different and consistent with the pore pressure gradient induced by the slow slip, as predicted by our poroelastic modeling of SSEs in Guerrero. A parametric study of the governing non-linear diffusion equation shows that pore pressure waves propagate, under realistic conditions (as settled by experimental rock tests), with the same speeds as those observed for the rapid tremor migrations (RTM) in Guerrero, Cascadia and Japan. This result suggests that physical conditions surrounding the plate interface (such as pore pressure gradients) are likely to produce pressure waves, and that these waves may be responsible for the RTM.

*J06-3-02
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ip to earthquake)

Comprehensive detection of low frequency tremor triggered by teleseismic surface waves in northern Kii and western Shikoku, southwest Japan

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Deep low frequency tremor is sometimes triggered by surface waves from teleseismic events. Such tremor is called as triggered tremor. In this study, we investigated finer spatiotemporal characteristics of triggered tremor to reveal its activity. We applied matched filter technique to detect triggered tremor in northern Kii and western Shikoku area in southwest Japan, where triggered tremor episodes were observed many times. We used waveforms of low frequency earthquakes based on the JMA hypocenter catalog as templates of tremor. We analyzed NIED Hi-net waveform data for 67 teleseismic events with magnitude larger than 7.5 after Dec. 26, 2004.
As a result, triggered tremor episodes were observed at 9 and 15 teleseismic events in northern Kii and in western Shikoku, respectively. The activity area was limited in one spot in northern Kii. In western Shikoku, two spots were activated by several teleseismic events, and either one of the two was by other events.
Along-dip migrations of triggered tremor were observed in both areas. Migration speed of triggered tremor is about 10 km/h in northern Kii and about 40 km/h in western Shikoku. In northern Kii, the directions of migrations are same in all cases. In western Shikoku, both up-dip and down-dip migrations were observed.
Although the estimated migration speed is much faster than that of episodic tremor and slip, about 10 km/day, tremor migration with similar speed to our result has been reported during non-triggered tremor in previous studies. In northern Kii, migration speed of triggered tremor is similar to rapid tremor reversal and rapid tremor forward (Houston et al., 2011). In western Shikoku, migration of triggered tremor is similar to rapid streak (Ghosh et al., 2010).
We considered models of the migrations of triggered tremor based on previously proposed models. The fluid model (Ghosh et al., 2010) and tremor asperity model (Ando et al., 2012) may be reasonable for migrations of triggered tremor.

*J06-3-03
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Analyzing tectonic tremor and low-frequency earthquakes' activity in western Shikoku using automatic detection and location scheme

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Slow earthquakes, spanning a wide range of duration and amplitude scales, unify a broad class of events generating seismic signals that are significantly different from classical earthquakes. These events include weak, long-duration and low-amplitude, nonstationary signals such as tectonic tremors, low-frequency earthquakes and very-low frequency earthquakes. While the physical mechanism underlying the generation of slow earthquakes is not fully understood, they are considered to represent different manifestations of the same process associated with fluid-enabled shear transients at brittle–ductile transition zones of active faults. The ability to outline in fine detail the space-time pattern of slow earthquakes' energy release activity and to clarify the relationship between its different components represents a key to understanding the physics of underlying phenomena.
We present here an automatic scheme for detection and location of tectonic tremor and low-frequency earthquakes based on the method of Poiata et al. (2016). The method is a computationally efficient array-type detection and location scheme making use of multi-scale, frequency-selective coherence of signals' statistical features recorded across the stations of seismic network. We demonstrate the efficiency of the automatic scheme in detecting large number of low-frequency earthquakes during the energetic tectonic tremor sequences in western Shikoku and providing the details about their space-time activity patterns (i.e., migration and tidal modulation). The obtained low-frequency earthquake catalogs are compared against the existing tectonic tremor catalogs, as well as the catalog of low-frequency earthquakes provided by JMA. We also discuss the potential capabilities of the developed system to provide a basis for continuous monitoring and characterisation of tectonic tremor and low-frequency earthquakes' activity.

*J06-3-04
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Continuous S-wave signals following 2014 Mw 6.8 SSE in the Hikurangi subduction margin offshore New Zealand

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From May, 2014, for about a year, marine seismic and geodetic experiment was conducted at the Hikurangi subduction margin. During this experiment, a Mw 6.8 SSE occurred from September through October, 2014, directly beneath the ocean bottom seismometer (OBS) network (Wallace et al., 2016). In this study, we used continuous waveform data recorded by these OBSs, and applied an S-wave splitting analysis (Ando et al., 1983) and a polarization analysis for monitoring S-wave signals. These methods have been successfully applied to waveform data from onshore seismic networks (Bostock and Christensen 2012; Ishise and Nishida 2015).

As a result, we detected the continuous arrival of S-wave signals that appeared to have started in the later half of the SSE. This continuous signal was identified as tremor and its source location was determined by the envelope cross-correlation method (Todd et al., 2017, in prep). Our result, however, suggests that these signals occur continuously rather than as sporadic individual events, and that they last for more than two weeks. Polarization directions change at the same time and remained stable through the two week duration. Our analysis requires less OBSs than other methods for monitoring such S-wave signal, which may enable us to detect as yet unidentified signals in the Hikurangi margin where seismic attenuation has been known to be large. Distribution of the OBSs detecting such continuous signals suggests that they were generated only around the subducted seamount adjacent to the slow slip area. This is consistent with the location of individual tremors identified with envelope cross-correlation methods (Todd et al., 2017, in prep). The slow slip along the plate interface circumvented the subducted seamount (Wallace et al., 2016). By considering our result with the slip distribution, we can put more constraints on relationship between frictional properties along the plate interface and its topographic features.

*J06-3-05
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ip to earthquake)

Micro low-frequency tremor activity near Japan Trench

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SSEs and low-frequency tremor have been observed near the trench by using ocean bottom observations, and these have been located in the updip portion of a coseismic slip area [Wallace et al., 2016; Yamashita et al., 2015]. In addition, Ito et al. [2015] observed tremor sequences from the excitation of ambient noise amplitude, accompanied with SSE in the source area of the Tohoku-Oki earthquake's mainshock. However, the signals observed within these sequences showed very weak amplitude and were observed at only one station, nearest to the Japan Trench. Here, we report on our detection of micro low-frequency tectonic tremor (mLFT) activity prior to the 2011 Tohoku-Oki earthquake near the Japan Trench by using modified frequency scanning method (mFSM) as applied to ocean bottom seismometers (OBSs) at a single station. The original frequency scanning method [Sit et al., 2012] proposed a tremor detection method of calculating envelope waveform ratios through different bandpass filters of broadband data in the Cascadia margin. We modified this analysis for short period OBS seismic data recorded at 17 OBSs deployed in an area near the trench axis offshore Miyagi Prefecture, northeast Japan. Three bandpass filters of 2–4 Hz, 10–20 Hz, and 0.5–1.0 Hz, corresponding to the dominant frequency band of tremors, local earthquakes, and ocean noise, respectively, were applied to the OBS records for a period between November 19, 2010 and March 9, 2011.
The results of applying the mFSM show three major tremor sequences, suggesting tremor activity in the shallowest part of the subduction zone. The sequences agree with the results of Ito et al [2015]. Furthermore, we successfully detected tremors at landward stations in the second sequence. We estimated the energy release from the envelope amplitude of two horizontal components filtered at 2-4Hz after removing site effects. The energy estimates are in general very weak, compared with tremors typically observed in other regions.

*J06-3-06
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ip to earthquake)

Rheologically controlled spatial separation of the megathrust seismogenic zone and the zone of Episodic Tremor and Slip

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Episodic Tremor and Slip (ETS) is the most peculiar type of slow slip event. While slow slips of various durations and magnitudes occur at all tectonic environments, ETS is the most abundant in subduction zones of young and warm subducting slabs such as Cascadia, Nankai, and Mexico. Adding to the peculiarity is a tendency to be confined to a narrow depth range around the tip of the mantle wedge. If the ETS zone is assumed to represent a transition from seismic to aseismic behavior, its spatial separation from the seismogenic zone makes it even more peculiar. Here we propose a thermo-rheological model to explain all these peculiarities, especially the separation of the two zones. The model consists of the following key components. (1) The dehydrating slab supplies ample fluids at shallow depths. (2) The tip portion of the mantle wedge is fully serpentinized, and slab-derived fluids precipitates large amounts of silica further updip. (3) Resultant permeability reduction around the wedge tip leads to locally very high pore-fluid pressure (Pf). (4) The seismogenic frictional behavior of the megathrust is terminated at a depth much shallower than the wedge tip. (5) But the very high-Pf around the mantle wedge tip gives rise to another, isolated friction zone responsible for ETS. (6) Separating the seismogenic and ETS zones is a segment of semi-frictional or viscous behavior that can produce long-term slow slip events. Using numerical calculation, we show that warm slabs provide favorable conditions for components (1), (2), and (4), leading to components (3), (5), and (6). We also show that under special geological circumstances, similar conditions may occur and promote ETS-like phenomena even without a warm slab, such as in Hikurangi, or even not in a subduction zone, such as along the San Andreas Fault. The new model reconciles a wide range of seemingly disparate observations and defines a new framework for the study of slip behaviour and seismogenesis of major faults.

*J06-4-01
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Renovated 3D image of Nankai accretionary wedge and shallow seismogenic zone off Kumano through reprocessing of 3D seismic data

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For the next stage of the deep scientific drilling in Nankai Trough seismogenic zone off Kumano, it is essential to obtain precise structural image and depth estimation around the mega-splay and the plate boundary fault, as well as fine structures in accreted sediments around the drilling site. In 2006, three dimensional multi-channel seismic data acquisition and processing were carried out. However, the obtained data could not necessarily resolve deep structures due to relatively short (4.5 km) streamers and due to the strong Kuroshio current.
In order to obtain the clearer depth image for the next deep drilling target, we decided to reprocess a part of the 3D volume with today's advanced technology. First, preprocessing with recent technologies of multiple elimination and broadband processing was applied in order to clarify reflection signals. Second, the pre-stack time migration for time domain imaging, the sophisticated velocity model building in depth domain, and the pre-stack depth migration were carried out to obtain the fine depth image.
Improved images in the shallow accretionary wedge reveal dynamic deformation features (e.g. branching of splay faults, thrusting of the lower Shikoku Basin formation, BSRs). Lower Shikoku Basin formation below the forearc slope area show anomalously low Vp, consistent with estimation by Park et al. (2010 Geology). Additional reflectors above decollements are identified in the formation.
Low Vp zone (<4km/s) spreads beneath the splay fault and above the top of oceanic crust, consistent with Kamei et al. (2012).
3D geometry of the megasplay fault below the southeastern Kumano Basin indicates a bending downward feature in its southeastern rim of reprocessed area. This bent area is overlain by an anomalously high-Vp volume (>5 km/s). We also identify a couple of landward-dipping reflectors in this high-Vp region. Careful inspection will modify or add these preliminary interpretations.

*J06-4-02
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ip to earthquake)

Evaluation of rock evolution process in seismogenic fault: Dynamic wave propagation modeling to the digitalized fault rocks

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To understand the characteristics of the Nankai seismogenic fault in the plate convergent margins, we calculated the P- and S-wave velocities (Vp and Vs) of digital rock models constructed from core samples of an ancient plate boundary fault at Nobeoka in Kyushu, southwest Japan. We first constructed 3D digital rock models from micro-CT images and identified their heterogeneous features (cracks or veins). We replaced the cracks and veins with air, water, quartz, calcite, and other materials with different bulk and shear moduli. Using the Rotated Staggered Grid Finite-Difference Method, we performed dynamic wave propagation simulation and quantified the effective Vp, Vs, and the ratio of Vp to Vs (Vp/Vs) of the 3D digital rock models with different crack-filling minerals. Our results demonstrate that the water-saturated cracks considerably decreased the seismic velocity and increased Vp/Vs. The Vp/Vs of the quartz-filled rock model was lower than that in the water-saturated case and calcite-filled rock model. By comparing the elastic properties derived from the digital rock models with the seismic velocities (e.g., Vp and Vp/Vs) around the seismogenic fault estimated from field seismic data, we characterized the evolution of the deep seismogenic fault. The high Vp/Vs and low Vp observed at the transition region from the aseismic to seismic regimes in the Nankai Trough are caused by open cracks (or fractures) while the low Vp/Vs and high Vp at the coseismic region suggests quartz-filled cracks. The results indicate that a great earthquake could occur in the coseismic region partially due to slip velocity weakening of friction coefficient of quartz.

Key words: Digital rock, wave propagation simulation, fracture-filled materials, and earthquake fault

*J06-4-03
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Down-dip variations in a subducting low-velocity zone linked to episodic tremor and slip

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Fluids are thought to play an important role in controlling episodic tremor and slow slip (ETS) in subduction zones. Therefore, constraining the along-dip distribution of fluids is necessary to better understand source mechanism of ETS, and particularly the role played by fluids in ETS generation. Here, we report clear observations of coherent ScSp phases with a dense seismic array in western Shikoku, Japan, where ETS has been most active over the past decade. Using numerical simulations of elastic-wave propagation to reproduce the observed ScSp phases, we demonstrate that, relative to shallow depths, either the Vp/Vs ratio or the thickness of a low-velocity zone (LVZ) within the subducting oceanic crust increases beneath the mantle wedge corner where ETS has been observed. In addition, amplitudes of receiver functions associated with the LVZ increase at deeper depths, which support the down-dip variations of structural elements. These depth dependences of the structural elements provide us with new evidence that either high-pressurized fluid is confined or that a wide ductile shear zone, lubricated by fluid, develops in the subducting oceanic crust at ETS source depths.

*J06-4-04
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Interplate thermal regime and slab dehydration at the source region of episodic tremor and slow slip events in the Cascadia subduction zone

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Giant earthquakes are considered to have occurred historically and may take place in a near future in the Cascadia subduction zone. In contrast to the cold and thick Pacific (PAC) plate subducted beneath the northeast Japan characterized by numerous interplate earthquakes and comparatively fewer slow earthquakes, the warm and hot Juan de Fuca (JF) plate subducted beneath the North American plate witnesses much more episodic occurrences of tectonic tremors and slow slip events (ETS), accompanying less regular earthquakes. This has enabled us to compare and understand the different generation mechanisms between regular and slow earthquakes. Possible candidates to interpret such differences may attribute to slab brittle failure largely determined by different slab thermal regime, while pore fluid pressure variation in the fractures greatly affected by slab metamorphism. We constructed a 3D time-dependent thermal convection model with a size of 1150*700*400 km along the Cascadia Trench, initiating subduction in the northeast direction with calculation time up to 15 Myr. The geometry of the JF plate has been prescribed, being based on the extrapolated data of Slab1.0. Results show a distinct 3D slab dehydration belt and temperature transition zone along the clustered hypocenters of episodic tremors immediately beneath Vancouver Island in the northern part and almost 100 km east of coast of Washington and Oregon in the southern part with temperatures of 500-700 deg. Water content in MORB decreased from 2 wt% to 0 wt%. Interestingly, megathrust earthquakes occurred mostly near the triple plate junctions, such as the JF-NA-Explorer and PAC-NA-Gorda plate junctions, and beneath Washington where slab convex portion exists. Regular earthquakes are fewer observed beneath Oregon. At the source region of ETS in Cascadia, the interplate temperatures of the JF plate are averagely 200-400 deg higher than those of the PAC plate beneath Japan at the same depth range.

The dynamic stiffness as the indicator of slip mode and transition of the fault to a metastable stage.

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Studied is the gradual transition from unstable to stable frictional sliding in laboratory experiment. The behavior of gouge-filled fault was investigated at the experimental setup based on the spring-bock slider model. We document transitions between different modes of sliding as the result of changing proportion of gouge components. The values of scaled kinetic energy typical for events inherent to those modes differ by several orders of magnitude, while differences in contact strengths and amplitudes of shear stress drops remain relatively small. The parameter of the fault, which is very sensitive to changes of gouge composition is the maximal rate of frictional resistance weakening ks. The obtained results allow concluding that the slip mode is controlled by the ratio of ks to the stiffness of enclosing rock massif.
The value of ks is closely coupled with the fault specific shear dynamic stiffness. The latter can be determined from measurements of the parameters of seismic waves passing through or reflected from a fault. The technique of stiffness estimation was developed in our previous studies and tested in laboratory and 'in situ' observations.
We document that the dynamic stiffness of model fault drop drastically before both stick-slip events and slow slip events. The Shear stiffness decrease begins long before the macroscopic displacement is recorded. In our experiments, the time of precursor manifestation was up to 1/3 of the duration of the “seismic cycle."
If similar mechanisms operate in nature, the effect of fault evolution to a metastable stage can be revealed through active and/or passive seismic monitoring of fault zones. This effect manifests both in the parameters of seismic waves reflected from the fault, and in the spectra of microseismic noise, which had already been registered before several powerful earthquakes.

*J06-4-06
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

1972 Slow Mega Slip Event in Mexico Recoded with Tide Gauges

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The aseismic slow slip events (SSEs) are essential elements of the seismic cycle of large thrust earthquakes in subduction zones. GPS networks so far are the main tools for the SSE detection. Tide gauges data may also provide useful information about large subduction thrust SSEs in the pre-GPS epoch (PGE).
Since 1997 there were five large Mw˜7.5, long-term slow slip events recorded by GPS in the the subduction zone of Mexico. Older SSEs are not detectable using campaign GPS measurements. Research quality tide gauge data in the Pacific coast of Mexico exists back to the year 1953 that gives a chance to recover the SSE in the PGE. Before a search for the PGE SSEs the monthly averaged tide gauge (TG) records had been processed to get rid of the long-term tide harmonics, partially reduced for the el Ninio effect, long-period solar harmonics were removed and the residual TG records smoothed.
There are two unconformities observed in the final reduced TG record at the Acapulco station in 1962 and 1972. The first step-like signal corresponds to the coseismic coastal uplift of ˜22 cm produced by a doublet of earthquakes with Mw 7.1 and 7.0 in May 1962 below Acapulco. The second distinct coastal rise of 10-12 cm lasted almost one year in 1972 without any noticeable seismic activity in Guerrero. The amplitude and time span of this event closely reminds recent long-term SSEs observed at the same area. Analysis of differential residuals (with respect to the Manzanillo) of TG records reveals similar concurrent but smaller amplitude coastal rise at Puerto Angel and Salina Cruz TG stations in the Oaxaca state. The records at TG stations located NW from the Acapulco do not show any anomalous signals corresponding to the apparent 1972 slow slip in Guerrero-Oaxaca.
Our result suggest that the along coast extent of the 1972 SSE may be about of 500 km, probably the largest subduction SSE recorded so far. The propagation of this event is difficult to assess based only on three TG records.

*J06-P-01
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Real-time slow slip monitoring with the Geodetic Data Stacking (GDS) method

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Japan Meteorological Agency (JMA) has been operating a strainmeter network to detect precursory phenomena of anticipated Tokai megathrust earthquake south off the central Japan. The network consists of 16 volumetric strainmeters and 11 multi-component strainmeters. We are performing 24-hour monitoring of strain change due to possible precursory slow slip events, or episodic ones, with correcting strain changes from the effects of barometric pressure, earth and ocean tides and precipitation in real-time mode.

Miyaoka and Yokota(2012) developed a new analyzing method that enhances signal-noise ratio (S/N) by stacking strainmeter time-series data of plural components. We call this method Geodetic Data Stacking (GDS) method.

If a slip does not spread out or migrate widely, time-series data are similar to each other in shape except for their polarities and amplitudes. Some data indicate positive changes (+: extensional) and others indicate the negative (-: compressional). We reverse the polarity of changes for the components that should show negative changes so that all the data should indicate positive polarities, and stack them. The component to be reversed is selected from calculated polarity with assuming a slip of small fault at each grid points on the plate boundary.

As the result, the signal component will be emphasized and S/N will be improved. Using this method, we are monitoring small short-term slow slip events as well as a pre-slip event in real-time. In addition, we detected the long-term slow slip event going on since 2013 and are monitoring that.

In the presentation, we would like to show the outline of the GDS method and some products.

*J06-P-02
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Construction of short-term slow slip event catalog detected automatically from tilt and strain data within the Nankai subduction zone, Japan

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In the Nankai subduction zone, a large amount of high-quality geodetic and seismic data enables us to study the slow earthquakes such as the slow slip events (SSEs) and the low-frequency tremors in detail. In order to reveal the source physics of various interplate slip phenomena, it is important to understand the relationship among members of slow earthquakes. Source models of SSEs estimated from geodetic data objectively and independently of seismic slow earthquake catalog (e.g., Kimura et al., 2011) are essential to clarify the relationship. We have developed an automated method to detect SSEs from tilt and strain data, and in order to apply the method to data with the length of one year or longer, it is necessary to treat temporal changes of background noise levels appropriately. To assume incorrect noise parameters is possible to cause a miss detection or an excessive detection.
In this study, we evaluate temporal changes in noise levels, and apply the automated SSE detection method to the 16-year-length data using the noise strengths. We assumed that continuous geodetic data contains background linear trend, random-walk noise and white noise, and estimated the noise strengths for a 30-day moving time-window using maximum likelihood method. Typical strengths of the random-walk and white noises are approximately 1.0-5.0 nrad/hr^0.5 and 1.0-5.0 nrad, respectively, for tilt data, and 0.5-1.0 nstrain/hr^0.5 and 0.5-1.0 nstrain, respectively, for strain data. The random-walk noise strengths of tilt data at MASH station in Kii Peninsula had been 1.0-2.0 nrad/hr^0.5 and almost constant from 2001 to 2012. They were increasing in 2013 and reached 10-20 nrad/hr^0.5. This increase in noise levels lowered the detection capability for SSEs in Kii Peninsula.
Based on the evaluated noise characteristics, we automatically select geodetic data with significantly low and stable noise levels for the SSE detection.
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*J06-P-03
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Shallow Slow Slip Event Off the Kii Peninsula, Japan

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On 1 April 2016, an earthquake (Mw=5.9, hereafter mainshock, USGS) occurred off the Kii Peninsula, Japan. The mainshock occurred around the expected focal region of the so-called Tonankai earthquake. After the mainshock, strain changes caused by the slow slip event (SSE) were observed by the three borehole strainmeters of AIST. The source region of this SSE is located on the plate interface at southeast side of the mainshock. An equivalent magnitude of this SSE is Mw 6.0, and duration is about 7 days. From after just a few days from the mainshock, in and around this SSE source region, intensive activity of shallow low frequency tremor (LFT) has been observed for about two weeks, it is assumed that these shallow tremor events were induced by this SSE.
In off the Kii Peninsula, SSE had not been observed by geodetic method. The slip deficit rate of this SSE source region is about 3 cm / year (Yokota et al., 2016), and the plate convergence rate is 5.0 to 6.5 cm / year (Heki and Miyazaki, 2001). Therefore, in addition to this case, there is a possibility that SSE frequently occurred in this region. To support of this hypothesis, VLF and LFT have been often observed in this area.
In this presentation, we will report the results of verifying other cases.

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*J06-P-04
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Spatio-temporal evolution of recurrent slow slip events from 2010 to 2013 along the Ryukyu Trench, southwestern Japan

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Various types of slow earthquakes, including slow slip events (SSEs, Heki and Kataoka, 2008, Nishimura, 2014), very low frequency earthquakes (VLFEs, Ando et al. 2012, Nakamura and Sunagawa, 2015), and low frequency earthquakes (LFEs, Nakamura, submitted), are detected along the southern part of the Ryukyu Trench, Japan. In this area, Global Navigation Satellite System (GNSS) stations have been newly installed since 2010 by Kyoto University in addition to the stations operated by Geospatial Information Authority of Japan. This study applies a modified Network Inversion Filter to these GNSS time series from March 2010 to February 2013, to estimate the spatio-temporal evolution of slow slip on the plate interface in detail. Five SSEs with Mw 6.6–6.8 and durations of 30–100 days are found during this period. The main slip region of the five SSEs are similar, located beneath the northwestern side of the Iriomote island. In contrast to the similarity in the spatial location, our detailed analysis newly clarifies the difference in the temporal evolution among the events; three SSEs suddenly accelerated to the maximum slip rate, and the other two SSEs showed a slow acceleration for 20–50 days. The spatial relationship among the SSEs, LFEs, VLFEs, and tsunamigenic earthquake, is complementary along the trench, depending on the depth; tsunamigenic region in the shallowest part, weakly coupled region of VLFEs and LFEs with depths shallower than 30 km, and SSEs deeper than 30 km, reflecting the depth variation of physical properties. VLFEs are sometimes activated 10–20 days after the onset of SSEs that initiate with slow acceleration phase, although the number of SSEs is too small to assert this correlation. Since new GNSS stations are planning to be established, additional data and further analyses will possibly make the correlation clear in the future.

*J06-P-05
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Estimation of the spatiotemporal evolution of slow slip events in the Tokai region, central Japan, since 2013 using GNSS data

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In the Tokai region, central Japan, the previous long-term slow slip event (L-SSE) occurred on the subducting Philippine Sea Plate (PSP) from 2000 to 2005. Moreover, many short-term SSEs (S-SSEs) have been observed in the Tokai region since 1996. Ozawa et al.(2016) reported that a SSE seems to have started in the similar area of the previous Tokai L-SSE in the beginning of 2013. We applied a time-dependent inversion method to GNSS data to obtain the spatiotemporal evolution of an L-SSE and S-SSEs on the PSP beneath the Tokai region, since 2013.
GNSS data from Jan. 1, 2008 to Dec. 30, 2015 were used in this study. The GIPSY-OASIS II software was used to estimate daily coordinates of 222 GNSS stations from the GEONET in the Tokai region. It is well known that GNSS time series have many systematic signals that do not result from SSEs. These systematic signals include, for example, seasonal variations and post-seismic deformation of the 2011 Tohoku-oki earthquake(Mw9.0). After removing these systematic signals, we applied a modified Network Inversion Filter (NIF) [Fukuda et al., 2008]. The original NIF [Segall & Matthews, 1997] assumes a constant hyperparameter for the temporal smoothing of slip rates and thus often results in oversmoothing of slip rates. The modified NIF assumes a time-variable hyperparameter, so that changes in slip rates are effectively extracted from GNSS time series.
The results indicate the moment magnitude and maximum cumulative slip of the SSE were estimated to be Mw～6.5 and ～6.5 cm from Jan. 1, 2013 to Dec. 30, 2015, respectively. In addition to the L-SSE from 2013 to 2015, two large S-SSEs were detected near the Ise Bay in the down-dip area of the L-SSE. Our results suggest that the slip peaks of the L-SSE and S-SSEs do not overlap and that the temporal variation of moment evolution in the central area of the L-SSE is smooth and is not affected by the S-SSEs. Low frequency tremors [Obara et al., 2010] do not occur near the center of the L-SSE.

*J06-P-06
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Estimating long-term and short-term slow slip events in the Bungo Channel area by MCMKF-based inversion.

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We estimated space-time evolution of long-term and short-term slow slip events (L-SSE and S-SSE, respectively) in the Bungo Channel region between Jan. 1, 2009 and Dec. 31, 2012, by employing the Monte Carlo Mixture Kalman Filter (MCMKF)-based Network Inversion Filter (NIF) [Fukuda et al.,2014]. We use GNSS time series at GEONET stations between Jan. 1, 2009 and Dec. 31, 2012 as provided by Takuya Nishimura [Personal Communication]. First we have pre-processed the original GNSS time series to remove secular velocities, annual and semi-annual variations, offsets associated with earthquakes and antenna changes and postseismic deformations. Then those pre-processed time series would contain only transient deformation and local benchmark wobble provided there is no other noise source. We inverted pre-processed GNSS time series to estimate transient slip on the plate boundary at the Nankai Trough. We employ plate configuration data by Hirose et al. [2008] and select the area of about 200km long to the east and 280km long to the north as the model region. We subdivide the model region into 719 subfault patches, and expand the slip by a series of 24 spatial depleted basis functions. During this period, in addition to a L-SSE that occurred for about one year, S-SSEs have been inferred in the eastern Shikoku and western Kyushu. The inferred L-SSE is consistent with previous studies such as Yoshioka [2015], and the timing and location of S-SSE is similar to those estimated by Nishimura [2014]. This is the first case that space-time evolutions of both L-SSE and S-SSE have been estimated in the Bungo Channel region from a single inversion analysis. In the presentation we will show the results in detail and discuss the similarities and differences between L-SSE and S-SSE.

*J06-P-07
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

A trial to find long-term variation in slip-deficits in the Bungo Channel region, Nankai Trough.

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We estimated space-time variation of secular slip and slip-deficits in the Bungo Channel region between two successive long-term slow slip events (L-SSEs) by employing the Monte Carlo Mixture Kalman Filter (MCMKF)-based Network Inversion Filter (NIF) [Fukuda et al.,2014]. We use GNSS time series at GEONET stations between Jan. 1, 2012 and Dec. 31, 2015 as provided by Takuya Nishimura [Personal Communication]. First we have pre-processed the original GNSS time series to remove secular velocities, annual and semi-annual variations, offsets associated with earthquakes and antenna changes and postseismic deformations. Then those pre-processed time series would contain only transient deformation and local benchmark wobble provided there is no other noise source. We inverted pre-processed GNSS time series to estimate transient slips, if any, and slip-deficits on the plate boundary at the Nankai Trough. Following Yokoi et al. [2017, this meeting], we employ plate configuration data by Hirose et al. [2008] and select the area of about 200km long to the east and 280km long to the north as the model region. We subdivide the model region into 719 subfault patches, and expand the slip by a series of 24 spatial depleted basis functions. Up to now only short-term slow slip events (S-SSEs) have been found, and long-term variation of slip deficits are within uncertainties.

*J06-P-08
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Slip velocities of early afterslips in northeastern Japan

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We focus on temporal evolution of early afterslip velocities following large interplate earthquakes (2003 Tokachi-oki, 2005 Miyagi-oki, 2011 Tohoku-oki (March 9), and 2011 Tohoku-oki (March 11)) in northeastern Japan. First, we obtain surface deformation data at an interval of 30 seconds about 2 days after the earthquakes, using GSILIB. Next, we invert slip velocities at the plate interface from the data. We find that initial velocities of the afterslips positively correlate with magnitude of the mainshocks. The initial afterslip velocities are four orders of magnitude lower than mean slip velocities of their mainshocks. The early afterslips decay almost linearly with time during the investigation periods. Besides, we check effects of viscoelastic relaxation of asthenosphere by a numerical simulation, and confirm that the viscoelastic relaxation effects are negligible during the investigation periods in a viscosity range larger than 10^18 [Pa s].

*J06-P-09
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Low-frequency earthquake distribution covered with undrained layer of the overlying plate along Tokai plate boundary of the Nankai subduction zone

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We have developed a novel method that uses a 3D array to detect the P and S waves of deep low-frequency earthquakes (LFEs) along the Nankai subduction zone. We tried to find their P and S wave pairs by using a 3D array (6 km x 4 km area) with 14 seismic stations in the Tokai area including ones with deep (600 m at the deepest) borehole seismographs. We observed remarkable LFE activity over November 10-30, 2010 and identified P and S phases of LFEs with high quality result by using a semblance method. Referring to those identified P and S phases we manually picked the arrival times of not only both P and S waves of the 3D array stations but also S waves and rarely P waves of Hi-net stations. Using the arrival times we relocated precise hypocenters of the 15 LFEs. Those hypocenters distribute in the depth range from 26 km to 34 km approximately along the plate boundary inclining in depth from 30 km to 32 km. We compared the distribution of LFEs with the observed P-wave (dVp) and S-wave (dVs) velocity perturbation cross-sections along the subduction zone. Most of the LFEs occurred in the areas with dVp and dVs lower than about -3% along the plate boundary. And in the overlying plate just above the whole of LFE distribution there is a thin (several km thickness) layer with dVp and dVs higher than about 3%. We interpret that the higher velocity layer corresponds to an undrained layer keeping high pore-fluid pressures for LFE activity along the plate boundary.

*J06-P-10
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Variation of deep low frequency tremor activity along dip direction in western Shikoku, southwest Japan

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It is reported that deep low frequency tremor occurs more episodically at the updip part of the tremor region compared to the downdip part in Shikoku in southwest Japan (Obara et al., 2010, 2011) and Cascadia (Wech and Creager, 2011). In this study, we focused on the updip cluster in western Shikoku analyzed in Obara et al. (2010) in order to investigate tremor activity in a finer scale along the dip direction.

We applied a matched filter technique (Shelly et al., 2007), using continuous seismic waveform data from 2013 to 2015 at 12 Hi-net stations, which are operated by National Research Institute for Earth Science and Disaster Resilience. Waveform data were bandpass filtered between 2 and 8 Hz. As template events, we selected several low frequency earthquakes located within a streak-like tremor cluster along the dip direction of the subducting plate from the catalog of Japan Meteorological Agency (JMA). We used the time window of four seconds from one second before the arrival time of S-wave detected by JMA at each station.

We found stepwise tremor activities at all spots corresponding to episodic tremor and slip (ETS), which recurs at intervals of about a half year in western Shikoku. At the northern (deeper) part, the number of detected events during ETS was smaller, and small tremor bursts were more frequently detected during inter-ETS compared to the southern (shallower) part. This result is consistent with the general trend of tremor activity in wider scale in southwest Japan and Cascadia.

Some tremor episodes were detected only at the up-dip part of the tremor cluster, although individual ETSs are mainly initiated at the deeper part and migrate upwards in western Shikoku (Obara et al., 2011) and Cascadia (Wech and Creager, 2011). This may suggest that some ETSs initiate at the updip part.

Seismic anisotropy monitoring and detection of tremor activity in the southwest Japan subduction zone

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We have been investigating the source region of Nankai trough mega-thrust earthquake from a view of seismic anisotropy. In this study, a seismic anisotropy monitoring, which is simultaneous continuous measurements using shear (S) wave splitting analysis and polarization analysis, was performed during tremor episodes at Hi-net stations developed in eastern Shikoku, southwest Japan. The method is similar to Bostock and Christensen [2012]. We inferred parameters of S-wave anisotropy (polarization direction of fast S wave and delay time between fast and slow S waves) and those of incoming wave (back azimuth and incident angle) using a 1 min long sliding window with 50% overlap. They reveal a close relationship among temporal variations of anisotropy, polarizations of incoming wave and spatial-temporal development of tremor activities. They show systematic changes during located tremor activities [e.g., world tremor database, Idehara et al., 2014].
We thus interpret monitoring the relationship among temporal variations of anisotropy, incoming wave, and tremor activity as a tremor detection method. That is, we assumed that the systematic change indicates occurrence of tremor. If so, it may be possible to detect occurrence of tremor by analyzing seismograms at a single station as well as detect occurrence of tremor, whereas commonly-used source location determination methods [e.g., Obara, 2002] require observation of coherent seismic signals at several stations.
Recently, we started to apply the monitoring method to ocean bottom seismometer data in order to investigate offshore tremor activity. Since the quality and quantity of marine observation data is limited in various aspects compared with those of land-based observation data, this will eventually discover some unknown phenomena. In this presentation, we show preliminary result of the monitoring using an offshore seismic network, DONET, off southwest Japan along the Nankai Trough.

*J06-P-12
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Low frequency tremor activity in the Tohoku subduction zone based on ocean bottom seismograms

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Various kinds of slow earthquakes have been found along the plate boundary zones in the world. In the Tohoku subduction zone, where slow event activities have been considered insignificant, low frequency tremors prior to the 2011 Tohoku-Oki earthquake and very low frequency earthquakes were identified by recent studies based on geodetic signals from seafloor pressure observations and onshore broad-band seismographs. In the Nankai subduction zone, records of ocean bottom seismometers(OBS) are proved to be effective for detecting low frequency tremors beneath the OBS networks. In this study, we try to detect low frequency tremors and to locate their sources using the OBS records deployed in the Tohoku-Oki.
As the initial trial, we focused on the continuous records on Dec. 2007 when VLFEs were previously detected by onshore broad band seismograms. We applied a envelope correlation method (ECM) to the short period OBS records obtained near the epicenters of VLFEs to detect tremors. Majority of the events detected by ECM seemed to be ordinary earthquakes containing a lot of high frequency signals. In order to identify tremors from the detected events, we calculated an amplitude ratio of the envelope in low frequency band (2- 8 Hz) to that in high frequency band (10- 20 Hz). As a result, we detected an event having significantly larger ratio than those of ordinary earthquakes at all OBS stations, as a possible candidate of a low frequency tremor event. After making visual inspection of the waveforms, we confirmed evident prevalence of low frequency contents and depletion of high frequency signals, as usually observed for low frequency tremors in general. The source was located just beneath the OBS network based on the relative arrival times, the larger amplitudes were observed at stations nearer to the located source. Therefore, the identified event is likely to be a low frequency event occurred in the vicinity of the location of the OBS network.

Low-frequency tremor activity in the shallow part of Nankai Trough and Ryukyu Trench revealed by long-term ocean bottom observation

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Low-frequency tremor is one of the slow earthquakes occurred in the deep and shallow part of the subduction zone. The detail of shallow tremor was documented by Yamashita et al. (2015), they have carried out the ocean bottom observation in the Hyuga-nada, southwestern part of Nankai Trough, and succeeded in detecting shallow tremor as a complete episode lasting for one month exhibiting similar migration property of deep tremor for the first time. From 2014, we started long-term ocean bottom seismological and geodetic observation in the Hyuga-nada. In addition, we also started that in the north part of Ryukyu Trench from 2014, in the central part of Ryukyu Trench from 2015.

During these observations, we found some tremor activities in those areas. In the Hyuga-nada, we detected tremor activity in 2014, 2015, and 2016. The 2016 activity may be triggered by 2016 Kumamoto earthquake. In the Ryukyu Trench, although it is hard to estimate the epicenter of tremor source because the separation between the ocean bottom seismometer is large, we found the locality of the shallow tremor activity.

From 2017, we started a new project for observation of shallow slow earthquake. We installed ocean bottom seismometers and pressure gauges around the focal area of shallow tremor in the Hyuga-nada. This observation will continue until 2020. For this presentation, we will introduce the ocean bottom observations and discuss the property of shallow tremor activity along the Nankai Trough and Ryukyu Trench using preliminary result by analyzing the data which were recovered from the ocean bottom.

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*J06-P-14
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Network-MT survey in the vicinity of area with a forthcoming slow slip event in the SW part of Shikoku Island, SW Japan

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In the Bungo channel region at the western margin of the Nankai megathrust rupture zones, the long-term slow slip events (SSE) repeatedly occurred about every 6 or 7 years and we expect the next event soon. The SSE also activate deeper episodic tremors and slips (ETS) on the plate interface.

In order to examine influence of interstitial fluids on occurrence of the SSE and/or ETS activities, we have started the Network-MT survey in the western part of the Shikoku Island facing the Bungo channel since April, 2016. We use metallic telephone line network of the Nippon Telegraph and Telephone Corp. to measure the electrical potential difference with long baselines of from several kilometers to 10 and several kilometers. We selected 17 areas in the western part of Ehime and Kochi prefectures and installed 3 or 4 electrodes in the respective areas. The electrical potential differences measured in this way are known to be less affected by small scale near-surface lateral resistivity heterogeneities. We also measure geomagnetic field at two stations in the target region. With the aid of the BIRRP code, we could estimate the frequency-domain response functions between each voltage difference and the horizontal magnetic fields from 5 s to 10^5 s. We will show spatial characteristics of the responses and their preliminary 3-D interpretation to estimate regional electrical resistivity structure with the aid of a DASOCC 3-D inversion code.

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*J06-P-15
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ip to earthquake)

Moment tensor inversion of tectonic tremors in the Guerrero subduction zone

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Slow earthquakes have exposed the actual complexity of the tectonic processes involved in subduction zones around the world. Despite different studies addressing these phenomena, its causal relationship is still debated.
Recent studies in different subduction zones suggest that tectonic tremors (TT) are caused by point dislocations at depth. Consequently, a systematic study of focal mechanisms of tremor sources turns out to be important to understand the processes that originate this phenomenon and the implications they have in the occurrence of slow earthquakes.
Cruz-Atienza et al. (2015) introduced the “Tremor Energy and Polarization" (TREP) method to locate tectonic tremors assuming horizontal point dislocations, which is a reasonable hypothesis for deep tremors in the state of Guerrero. However, this assumption could be a limitation in other cases where the fault dip is different (i.e., San Andreas Fault). The simultaneous determination of tremor locations and focal mechanisms would allow studying this phenomenon in any tectonic environment.
In this work, we generalize the TREP method employing a global inversion technique (i.e., simulated annealing) to determine simultaneously the source location and the associated moment tensor from the energy spatial distribution and the azimuth of the particle motion polarization.
Although the method has some difficulties to resolve the focal mechanims because of the ambient noise, preliminary results employing real data in Guerrero show that most of the obtained mechanisms are consistent with the geometry of the plate interface and with the plate convergence direction, which are similar to those reported for LFEs (Frank. et al 2013) and VLFs (Maury et al. 2016) in Mexico.

*J06-P-16
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Anisotropy in the subducted oceanic crust and the overlying continental crust coincides with slow slip phenomena in the flat portion of the Mexican subduction zone.

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A novel approach has been developed to isolate the anisotropy observed by receiver functions (RF) into the separate layers through which the seismic waves pass (Castillo et al., 2017). This approach has proven particularly effective in the Mexican flat slab, which remains in near contact with the continental crust to 300 km from the trench. There are 3 regions that can be observed with this approach: (1) The lower subducted oceanic crust; (2) the remnant mantle wedge between the oceanic and continental crust; and (3) the continental crust. Slow earthquakes are also found in the flat slab region, and they strongly correlate with changes in the anisotropy in the different layers. The flat slab region is a double slow earthquake zone: from updip to down-dip (1st slow earthquake zone) Mw ~7.5, 4-year recurrence-time slow slip events (SSE) with little tectonic tremor (TT) on the down-dip edge; and (2nd slow earthquake zone) Mw < 6.5, 2 – 3 month recurrence-time SSEs with a large amount of TT on down-dip edge. The highest anisotropy percentage in the subducted crust aligns with the TT in the two slow earthquake regions. In the remnant mantle wedge, high anisotropy only aligns with the TT in the second slow earthquake region. The overlying crust is the reverse with low anisotropy directly above the TT in each of the slow earthquake regions. This pattern may be explained by a seal at the base of the continental crust (fluids trapped beneath the crust where the TTs are located, leading to high anisotropy beneath the seal and low anisotropy above) broken by SSEs (high anisotropy above the SSEs and low anisotropy beneath as fluids are transported into the upper crust). The anisotropy direction changes with distance from the trench and correlates with LFE activity, but it is difficult to explain at this time.

*J06-P-17
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

The long duration, April 18, 2002 (Mw 6.7), Mexico earthquake; a small tsunami earthquake next to the Guerrero Gap

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We estimate the duration, extent and rupture velocity of the April 18, 2002 (Mw 6.7) earthquake. The hypocenter location (Pacheco & Singh, 2010) is inside what is known as the Guerrero Gap, a segment of the Mexican subduction zone that has not had a large earthquake in at least 100 years.
The 2002 earthquake is anomalous in the sense that it produced very small accelerations for its size (Iglesias et al 2003) and it is one of the earthquakes with longest duration relative to its magnitude recorded globally in the last 40 years (Duputel et al, 2013). Events of this type are particularly hazardous because they produce relatively large tsunamis (Kanamori, 1972) and small ground motions for their size, so they may be mistaken for smaller events by people near the coast, who may not prepare for the large tsunami. As near trench earthquakes are relatively rare, and due to their destruction potential, it is important to study in detail the few recorded events of this type.
The extent of the rupture area of the 2002 earthquake, is key to understanding the seismogenic potential of the Guerrero Gap. Often the rupture area of an earthquake is estimated by the extent of the aftershock area. However, locating earthquakes near the trench is difficult, due to their emerging P-waves and as they occur outside of the network of observation. In this study we calculate the duration of the 2002 earthquake by observations of far-field records. We use the difference in time between the first and last coherent signals in the peculiar P wavetrain of event, observed to conclude that the rupture had a duration and along strike length of approximately 56s and 60 km, respectively. The rupture propagated to the north-west with a rupture velocity of 1 km/s. To put further constraints on the rupture area, we relocate the aftershocks, using a relative location method (Cleveland & Ammon, 2013), based on cross-correlation of surface waves. Finally we discuss the implications of our results.

*J06-P-18
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Trench-parallel sliver motion in the Mexican oblique subduction zone

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Large, equivalent to Mw˜7.5, subduction thrust slow slip events (tSSE) in Guerrero, Mexico have a period of ˜4years. The secular GPS velocity vectors are oblique to the Middle America trench (MAT). The lateral velocity components abruptly diminish to the north by 4-5mm/year across La Venta-Chacalapa fault zone (LVC), striking along the Pacific coast of Guerrero and Oaxaca for ˜650km. This velocity slump reveals a partitioning of the oblique convergence between the Cocos and North America plates with a sinistral motion of the Xolapa forearc sliver.

Long-term GPS records show that the tSSEs are accompanied by strike-slip SSEs (sSSE) on the LVC fault. GPS displacement records in Guerrero reveal that during the interSSE periods (˜3 years) the LVC fault is mainly locked, and the shear strain rate across it remains constant at ˜14nrad/year. During the tSSE there is an increase of lateral sinistral displacement of the GPS stations on the coast, south of the fault while the stations to the north off the LVC undergo minor dextral displacements. The secular shear strain rate drastically changes across the fault from 64 nrad/year south of it to 11nrad/year to the north. The LVC fault is currently active but the slow accumulation of shear strain on it is periodically interrupted by sSSEs highly synchronized with the tSSEs.

According to the analysis of thrust events from local catalogs slip vectors lay between the vectors of plate convergence and trench normal. Obliquity of thrust slip vectors (1-5') grows southward along the coast. The oblique subduction motion is partitioned into trench parallel displacement along LVC fault zone at the rate of ˜8mm/yr. Secular trench parallel velocity calculated from GPS data is ˜6.5mm/yr. Slower motion at the surface (GPS) compared to the subduction interface (thrust events) may be due to the properties of the media.

*J06-P-19
Joint Symposium / J06. The spectrum of fault-zone deformation processes (from slow sl
ip to earthquake)

Drilling into Active Faults - In-situ Investigations on the Mechanics and Structure of Faults in Central Japan

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The drilling is of great advantage to study on the mechanics and structure of fault. We did integrated investigations on active faults in central Japan by drilling into the faults, in-situ downhole measurements and core observations. Those faults have different elapsed time since the last earthquakes; Nojima fault, the 1995 Hyogo-ken Nanbu Earthquake, M7.2 (Kobe Earthquake); the Neodani fault, 1891 Nobi earthquake (M=8.0); the Atera fault, 1586 Tensho earthquake (M=7.9); the Atotsugawa fault, 1858 Hida earthquake (M=7.0); the Gofukuji Fault that is said to have activated more than a thousand years ago.
In-situ stress measurements indicate the maximum horizontal compressive stress was nearly perpendicular to the fault strikes as for Nojima Fault case, but for other fault cases, the orientation of the maximum horizontal compressive stress was oblique to the fault strike. These results support the idea that the differential stress is small at narrow zone adjoining fracture zone and fault is quite weak after the earthquake. On the other hand, the frictional strength is still high outside the narrow fractured zone. The shear stress is as the same level as the frictional strength of host rock of the fault. Downhole logging and macro- and micro-scopic observation of recovered cores indicate complicated and internally hierarchical fault zone structure. Sets of narrow hardly fractured zones with adjacent broad weakly fractured zones are distributed within the fracture zone. The narrow hardly fractured zones are characterized as low electrical resistance, low density, low P-wave velocity, and high porosity. Fault seems not to have slipped on a specific plane, but on several fault planes at different earthquakes in the past. The complicated fault zone structure should have formed progressively during repeating earthquake. The stress state and structure of different faults seem to reflect different stage in earthquake preparing process in the earthquake recurrence cycle.

*J07-1-01
Joint Symposium / J07. Tracking the sea floor in motion

Observational Results of Seafloor Crustal Deformation Near the Nankai Trough Axis

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The Central Disaster Management Council, Japanese government extended the presumed source region of the Nankai mega-thrust earthquake to the trough axis in 2012. It is, therefore, essential to understand interplate locking condition near the trench axis, also for the anticipated mega-thrust earthquake at the Nankai Trough.
We installed three seafloor benchmarks for the seafloor crustal deformation measurement with the GNSS/acoustic technique in the vicinity of the Nankai Trough axis. Two benchmarks, TCA and TCB, are located about 15 and 35 km landward from the trough axis on the Amurian plate, respectively. The other benchmark TOA is located about 25 km seaward from the trough axis on the subducting Philippine Sea Plate. We can directly “measure" the slip deficit and the motion of the subducting Philippine Sea Plate through observations at the three benchmarks.
We performed campaign observations seven times at TCA and TOA benchmarks, and six times at TCB until the end of 2016. The worm ocean current, Kuroshio, flows over the observation sites, and we estimated heterogeneity of sound speed in the sea for the precise seafloor benchmark positioning. We, then, derived steady horizontal displacement rate with relative to the Amurian Plate from the time series of benchmark coordinate. The horizontal displacement rate is measured at 56+/-21 mm/y in the direction of N69+/-14W at TOA benchmark. The predicted motion of the Philippine Sea Plate is 60-61 mm/y in the direction of N59W at the position of TOA benchmark, which coincides with our measurement at TOA within the error interval. The measured horizontal displacement rates are 38+/-19 mm/y toward the west-northwest and 72+/-25 mm/y in the direction of N48+/-21W at TCA and TCB benchmarks, respectively. These results are the strong evidence for interplate locking, with coupling ratios of more than 40% on the basis of the back-slip model, at the most-shallowest segments of plate interface.

*J07-1-02
Joint Symposium / J07. Tracking the sea floor in motion

Interseismic seafloor GPS-A data used for tsunami generation modeling along the Nankai trough, Japan

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Dense near-fault GPS-A seafloor geodetic and on-shore GPS GEONET observations provide significantly improved resolution of the interseismic slip deficit in the Nankai trough, Japan [Yokota et al., 2016]. In a previous study, we included additional seafloor data at the Kumano basin collected by Nagoya University [Tadokoro et al., 2012] to estimate expected seafloor deformation during a large subduction zone earthquake as input to tsunami models [Watanabe et al., 2016 AGU]. In order to derive the appropriate model, the displacements caused by episodic events should be quantitatively estimated. Therefore, we first constructed a 3D FEM model to quantify the postseismic displacements following the southeastern off the Kii Peninsula earthquakes (on Sep. 5, 2004 JST, M 7.1, 7.4). Because these events occurred near the trough axis, the larger deformation was caused on the seafloor in the Kumano basin. Our results indicated that the displacements of up to 1 cm/year occurred in the period of July 2006 to July 2009 at the GPS-A sites. The corrected displacements were aligned to the Nankai-block (forearc sliver) to derive the slip deficit from the tectonic model of Loveless and Meade [2010]. For the slip deficit estimation, we modified the static model approach of Melgar and Bock [2013] using Okada's Green's functions. The plate interface was divided into approximately 25 x 25 km rectangular subfaults with displacements constrained to minimize Akaike's Bayesian Information Criterion. We then estimated the coseismic motions assuming that the 100-years of slip deficit was released instantaneously. These were then used as the initial conditions to model the propagation of the subsequent tsunami. In the presentation, we will show the updated distribution of the slip deficit rate in the Nankai trough region and the tsunami model.

*J07-1-03
Joint Symposium / J07. Tracking the sea floor in motion

Postseismic deformation of the 2011 Tohoku Earthquake measured by GPS/Acoustic observations

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The postseismic displacements after the 2011 Tohoku Earthquake measured by offshore geodetic studies [e.g., Watanabe et al., 2014] unveiled a deformation pattern significantly different from that onshore geodetic observations showed [e.g., Ozawa et al., 2012], which provided strong constraints on modeling postseismic deformation processes [e.g., Sun et al., 2014, Nature]. Furthermore, Tomita et al. [2016] revealed the along-trench variation of the postseismic displacements from GPS/Acoustic (GPS/A) observations. In this study, we show updated results of the GPS/A observations and discuss the spatiotemporal variation of the postseismic deformation.
We have carried out repeated campaign surveys from Sep. 2012 to Sep. 2016 at 20 GPS/A sites located in Tohoku-oki region. We estimated the displacement at each site for each survey by means of Kido et al. [2006] and then estimated the horizontal postseismic displacement rate at each site.
The displacement rates demonstrate clear spatial variation: slight trenchward motions (<˜5 cm/yr) in the north region of the primary rupture area (PRA), significant trenchward motions (5-15 cm/yr) in the south region of PRA, and significant landward motions (10-15 cm/yr) above PRA. The observed landward movement can be roughly explained by the viscoelastic relaxation model (VR model, Sun et al., 2014), but it cannot be fully accounted for, which may indicate a contribution of interplate locking producing further landward motions. In the north region of PRA, both of the observed and the VR modeled motions are small. This suggests trivial contributions of other processes (e.g., afterslip and interplate locking). In the south region of PRA, the observed trenchward motions are much larger than the VR modeled motions. It indicates that the contributions of afterslip is major in this region with showing temporal decay of afterslip, while such a temporal decay is not detected where contributions of the viscoelastic relaxation are dominant.

*J07-1-04
Joint Symposium / J07. Tracking the sea floor in motion

Preliminary Results of Realistic Interseismic Modeling and GPS-Acoustics Measurements on the Continental Slope of the Cascadia Subduction Zone

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Land-based GPS measurements suggest the megathrust is locked offshore along the Cascadia Subduction Zone. However, land-based data alone lack the resolution to constrain the how the slip deficit is distributed. Current efforts to constrain offshore crustal deformation using the GPS-Acoustic technique motivates refined, and more realistic models of the prism and forearc. Here we expand on efforts to create realistic, physics-based models of the deformation of the shallow subduction system. Our goal is to study what the relative importance is of different physical processes at play in the interseismic period, such as viscoelasticity of the upper mantle and plasticity of the wedge. In anticipation of renewed interest in expanding GPS-A studies in Cascadia, we have begun to use such realistic physics based models of the deformation of the shallow subduction system to make recommendations on what the optimal distribution of seafloor benchmarks should be in order to provide the most cost efficient solution to imaging the state of locking of the megathrust.

Here, we also discuss updates to current efforts to expand GPS-A coverage in Cascadia by utilizing Wavegliders to dramatically reduce ship costs. In July 2016, the GPS-A Wave Glider was launched on a month-long mission to two sites on the continental slope of the Cascadia Subduction Zone. One site is approximately 45 NM offshore central Oregon and the other approximately 50 NM offshore central Washington State. We will report on initial results of the GPS-A data collection and operational experiences of the mission. Wave Glider based GPS-A measurement have the potential to significantly increase the number and frequency of measurements of strain accumulation in Cascadia Subduction Zone and elsewhere.

*J07-1-05
Joint Symposium / J07. Tracking the sea floor in motion

Short-period ocean fluctuation induced by internal wave and its effect on GNSS/acoustic analysis

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In the GNSS/acoustic measurement, monitoring the fluctuation of water column in ocean, hence sound speed structure, is crucial to achieve high precision positioning. In the most case, ocean condition is approximated by time-varying stratified structure, which can be simultaneously solved with horizontal position of the seafloor transponder array using traveltimes at least from three transponders. However, non-negligible amount of horizontal variation of ocean structure often appears, effect of which (~30 cm) is usually cancelled out (~5 cm) by taking very long (~12 hour) time averaging. Kido et al. (2007) proposed that horizontal variation of the ocean structure can be considered employing five or more transponders at once if the structure is expressed by two quantity, i.e., horizontal gradient. However, this hypothesis requires that the variation must has a large spatial scale (> ~2-5km) so that the horizontal variation can be regarded as linear within the extent of acoustic path to seafloor transponders.
We have conducted several times of intensive XBT (eXpendable Bathy-Thermograph) casts in the past surveys, each of which consists of 12 times of profiling at 5-10 minute intervals. After correcting XBT sensor bias both in temperature and fall-rate, fluctuation of vertically integrated sound speed (= nadir total delay) well coincides with the GNSS/acoustic estimate in the 0.1 msec level. At the same time, apparent fluctuation in the horizontal array position is often observed. In the extensive XBT profiling, we found short period vertical oscillation of water column that amounted up to 20 m, which can be interpreted as internal gravity wave passing through the observation site. With density profile in the water column by XCTD cast, we can roughly estimate typical time period of the internal wave and hence the wavelength. This will be key quantity whether the horizontal variation can be approximated by linear structure.

*J07-1-06
Joint Symposium / J07. Tracking the sea floor in motion

Refining ship navigation with precise point positioning to measure seafloor displacement using repeated sidescan sonar surveys

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Accurate seafloor geodetic methods are critical to the study of marine natural hazards such as megathrust earthquakes, landslides, and volcanoes. Digital image correlation of repeated sidescan sonar surveys has been demonstrated as a technique for measuring seafloor displacement that is both economical and capable of obtaining measurements accurate to the meter scale regardless of seafloor depth. However, previous studies have been performed using ship navigation accurate to 0.5-0.7 meters and may drift on the scale of 1 meter per hour; these biases are likely expressed as noise in the displacement measurements. Precise point positioning is a GPS processing technique whereby satellite parameters are solved for using a pre-existing network of stations; these parameters can then be used to quickly and accurately solve for the position of additional GPS receivers. This technique is particularly well suited for processing ship GPS systems in very remote locations that may make differential GPS processing difficult. We perform precise point positioning using the kfPANDA package to improve our knowledge of the ship position during sets of repeated multibeam sonar surveys from two cruises, the May 2016 RR1605 cruise south of Palau and the February 2017 SR1704 cruise offshore San Diego, California. Using the improved navigation, we assess the accuracy of seafloor displacement measurements made from digital image correlation of repeated sidescan surveys for ship speeds of 4-6 knots and sonar frequencies of 12 kHz and 70 kHz.

*J07-2-01
Joint Symposium / J07. Tracking the sea floor in motion

New Technologies for Seafloor Deformation: Optical Fiber Strainmeters and Self-Calibrating Pressure Recorders

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We have advanced two new technologies for studying the deformation of the seafloor. The first is the measurement of strain using an optical fiber stretched horizontally across the seafloor. In October of 2015 we deployed a 200 m long optical fiber strainmeter at the toe of the accretionary prism of the Cascadia Subduction Zone off the coast of Oregon. The instrument was installed on the seafloor between two 100 kg anchors, tensioned, and operated continuously for 96 days. A temperature compensation scheme using two optical fibers with contrasting temperature responses allowed the separation of optical path length changes due to temperature from those due to strain. After removal of drift, an RMS noise level of 36 nanostrain over a one month record indicates the sensors will be useful for detecting slow slip events.

The second technology relies on seawater pressure as a proxy for height measurements. While time varying seafloor pressure can detect vertical motions with sub-centimeter precision, it is difficult to separate gauge drift from secular deformation. The Self-Calibrating Pressure Recorder (SCPR) was designed to circumvent the problem of gauge drift by employing an in situ deadweight calibrator to periodically provide a stable reference pressure to estimate and correct for gauge drift. One such instrument was deployed at Axial Volcano, collecting a continuous, drift-corrected recording of pressure for 17 months. In another experiment we are deploying an SCPR in campaign mode, collecting absolute pressure measurements at a series of seafloor benchmarks. We expect the method to yield epoch pressure values accurate to the equivalent of about 1 cm in height.

*J07-2-02
Joint Symposium / J07. Tracking the sea floor in motion

Initial characteristics of LTBMS borehole sensors installed in the Nankai Trough, Japan

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In the Nankai Trouhg area, the subduction of the plate has caused repeating great earthquakes along mega-thrusts faults between plate interfaces. We have planned to install long-term borehole monitoring system (LTBMS) in the Nankai Trough to monitor seismic activity for elucidating the generation process of the mega-thrust earthquake in the subduction zone. As first LTBMS site in this area, the C0002G observatory was activated on January 2013. In April and June 2016, the second LTBMS observatory, C0010A was successfully installed in the Nankai Trough, and was connected to DONET seafloor cable, respectively. The LTBMS observatory has a sensor suite comprising a broadband seismometer, geophone, accelerometer, volumetric strainmeter, tiltmeter, pressure gauge, and thermometer. These sensors were designed to collect weak and broadband signals that cannot be captured by land and/or seafloor observatories. After the installation and connection, realtime multi-borehole data via DONET seafloor cable network are available. In this presentation, we report initial characteristics of LTBMS sensors after the cable connection. The results includes: 1) Power spectral density analysis calculated from short-term records. 2) Running spectrum analysis using continuous long-term data. 3) Estimation of sensor orientation. 4) Initial drift and long-term stability of geodetic sensors. We compared PSD plots calculated from ambient noise records observed by C0002G, C0010A and DONET seismometers. Results confirmed that borehole seismometers are now functional to detect very weak seismic signal, such as VLF events. We also summarized initial response of tiltmeter and volumetric strainmeter, which can be used to detect weak geodetic signals as co-seismic events. Now auto evaluation processes are running on the data storage server not only to monitor sensor characteristics, but also to analyze very small seismic and geodetic events that are captured only by the LTBMS sensors.

*J07-2-03
Joint Symposium / J07. Tracking the sea floor in motion

Laboratory experiments for evaluating long-term characteristics of pressure sensors used for seafloor pressure monitoring

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Lots of precise pressure sensors are currently used for seafloor pressure monitoring to detect tectonic movements. Although the pressure sensors show high resolution and good stability, long-term fluctuations have been observed in the sensors' outputs during seafloor measurements, and their magnitudes are at the same level as the pressure change caused by tectonic movements of interest. Evaluating and compensating the effects of the long-term characteristics of the sensors are indispensable to improve the accuracy of the seafloor pressure measurement over years.
In this study, the long-term characteristics of quartz Bourdon-tube pressure sensors have been evaluated at the pressure calibration laboratory in National Metrology Institute of Japan. The pressure of 100 MPa has been applied to the test pressure sensors for a long period of time, during which calibrations are repeated at 100 MPa using a pressure balance as the standard. The calibration results, the deviation of the sensor's output from the standard value, at 100 MPa rapidly changed immediately after the pressure application, and then, the change rate became small and almost constant as time proceeded. This long-term behavior was quite different from that obtained for the same kind of sensors used under normal, atmospheric pressure conditions. The changes in the sensor's outputs at atmospheric pressure, intermittently obtained during the pressure application, showed that the observed long-term behavior at 100 MPa can mainly be attributed to the zero drift of the sensor.
On the basis of the results from laboratory experiments for over two years, measures are proposed and discussed to appropriately compensate the long-term characteristics of pressure sensors used for seafloor pressure monitoring.

*J07-2-05
Joint Symposium / J07. Tracking the sea floor in motion

Studying fault slip during and after the 2012 M 7.6 Costa Rica earthquake using land-based GNSS and near-trench fluid pressure observations

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Knowing whether the subduction fault slips to trench during or after an earthquake is important to the study of fault mechanics and tsunami generation, and it requires near-trench geodetic observations. In Costa Rica, two CORK borehole observatories were installed <1 km apart on the seaward and landward sides of the trench. During the 2012 M 7.6 earthquake, seafloor pressures on the two sides showed no relative change, indicating that rupture was limited to the epicentral area near the coast. Starting from 1.5 days after the rupture, several episodes of uplift of the subduction prism toe were observed as inter-site seafloor pressure changes. This uplift was accompanied by a subseafloor pressure rise (contraction) within the prism toe and a pressure drop (dilatation) within the incoming plate, suggesting pulses of afterslip propagating to the trench along the plate interface. Over >1 years, this uplift showed the same temporal characteristics as GNSS time series recorded on land, implying that the offshore and onshore deformation was controlled by the same afterslip process. We use both data to determine the co- and post-seismic slip distributions of this event. For the coseismic deformation, peak slip of ˜5 m is determined at a depth of 25-30 km. Calculation of shear stress change on the subduction fault suggests up to 8 MPa stress drop in the rupture zone but stress increase (<1 MPa) further updip. Afterslip is found to be shallower than the coseismic rupture with a cumulative peak (>1 m over 1.3 years) located in the area of coseismic stress increase just offshore and fairly large slip (˜0.7 m) at the trench. While postseismic stress decrease occurs at shallow depths, stress variation near the trench is smaller because of the low rigidity of sediments. The trench-breaching afterslip in Costa Rica, together with the trench-breaching rupture in the 2011 Tohoku-oki earthquake, provides important information on the slip behaviour of the shallowest part of megathrusts.

*J07-2-06
Joint Symposium / J07. Tracking the sea floor in motion

On the Interpretation of oceanic variations in terms of ocean bottom pressure

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To extract the pressure change due to crustal deformation from Ocean Bottom Pressure Record, it is essential to understand exactly what caused the observed pressure change. In this study, we consider about the factor of sea floor pressure change, especially temporal variation of several months to annual cycle from observed data. In this study, we use observed pressure records which spanned from June 2014 to June 2016 at off the coast of north island in New Zealand and Kumanonada using independent type Ocean Bottom Pressure Recorders. By using Baytap-G, we calculated the tidal component and subtracted it from the raw data. Then, we calculated sea-level anomaly (non-tidal oceanic variation) driven by air pressure and wind using barotropic ocean model. Comparing with Ocean Bottom Pressure Record after removing tidal component and calculated sea-level anomaly using ocean model, we found that there is a long-term component included in the Ocean Bottom Pressure Record that cannot be expressed by calculating ocean model. This long-term component's amplitude is about 1.5hPa and has about a 90-day cycle. In evaluating the pressure change derived from crustal deformation due to SSE, the amplitude of this component we detected in this study cannot be ignored. In this study, we consider the origin of this tong-term component from multiple viewpoints such as gravity observation satellite GRACE or tide gauge record etc. As a result, we found that there is a “fluctuation" which can be approximated as summation of harmonic mode. After subtracting the long-term component we identified in this study, we detected crustal deformation due to SSE at off the coast of north island in New Zealand. Then, we estimated fault slip due to the SSE from vertical displacement observed by Ocean Bottom Pressure and horizontal displacement observed by GNSS.

*J07-3-01
Joint Symposium / J07. Tracking the sea floor in motion

New buoy platform system for crustal displacement observation

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It is known that huge earthquakes occurred repeatedly around the Nankai Trough area and that coastal residents have received severe tsunami damages. The huge tsunami was brought by vertical displacement of the seafloor. Therefore, it is very important for local residents to receive the tsunami detection, to escape from tsunami and to evaluate crustal displacement. However, there are areas without the monitoring system like the dense oceanfloor network system for earthquakes and tsunamis (DONET). Therefore, we has developed a new buoy platform system for observation of tsunami and crustal displacement for five years. The large merit of the buoy platform is mobility and easy replacement. The system has a pressure gauge and acoustic transponders on the seafloor to observe crustal displacement and tsunami, and their signals are sent to our land station via the buoy using acoustic transmission and the iridium communication. Because it measures sea surface height using GNSS, the vertical crustal displacement can be also measured using the height and pressure gauge data. The buoy plays a role as the center of this system, which control timing to send acoustic signals, collect data from the seafloor and transfer the data to the land station. The buoy has to stand up to severe environment with sever typhoons and strong sea current with a speed of over 5 knots to realize long periods observation of the crustal displacement. To overcome above conditions and difficulties, we adopted some unique means for the system. Important technologies of this system are acoustic transmission between seafloor and the buoy, slack mooring to bear strong sea current, and the system stability. We introduce collected data and our remaining tasks currently for long observation under the severe conditions.

*J07-3-02
Joint Symposium / J07. Tracking the sea floor in motion

S-net project: Large-scale seismic and tsunami observation system on seafloor along the Japan Trench

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Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net) has 150 real-time monitoring observatories that cover the area about 1000km x 300 km from off-Hokkaido to off-Kanto. It is expected that early tsunami and earthquake warnings and earthquake researches will be enhanced. S-net consists of six segment networks of about 25 observatories and 800 km fiber optic cable (1,500 km fiber optic cable for the Japan Trench outer rise segment network). Each observatory has four sets of three-component seismometers for earthquake observation and two sets of pressure gauge for tsunami observation. Fiber-optic cable connects to landing station, and the data is transmitted from landing station to the data center via IP-VPN network.

S-net project has started in 2011. We have already finished deployment of all of the observatories and fiber-optic cables in 2016. We have also constructed five landing stations; Minamiboso station in Minamiboso City, Chiba Pref., Kashima station in Kashima City, Ibaraki Pref., Watari station in Watari Town, Miyagi Pref., Miyako station in Miyako City, Iwate Pref., and Hachinohe station in Hachinohe City, Aomori Pref.. The Watari station is located on the third floor of reinforced concrete building, and other stations are container-type data centers. The S-net (except outer-rise segment) started to operate in May 2016, and the pressure gauge and accelerometer data have been transmit to Japan Metrological Agency (JMA) for monitoring purpose. The S-net detected many earthquakes. S-net also observed tsunamis like with the earthquake of the November 22, 2016 off Fukushuma (M7.4).

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Joint Symposium / J07. Tracking the sea floor in motion

Real-time observation system of pressure gauges and accelerometers on seafloor using ICT through seafloor fiber cable installed in the off-Sanriku region, Japan

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A seafloor cabled system is useful for study of earth science and disaster mitigation, because real-time and long-term observation can be performed. A new system has been required from views of costs and flexibility of measurements. We have been developing a system using Information and Communication Technologies (ICT) for data transmission and system control. The new system has flexibility since software processes various measurements. Reliability of the system is kept by using redundant system which is easily constructed using the ICT. The first system based on this concept was deployed in Japan Sea. Development of the second system started in 2012. The second system has both seismometers and pressure gauges. An observation node has a CPU and FPGA, and the system uses standard TCP/IP protocol with a speed of 1 Gbps for data transmission, system control and monitoring. IEEE-1588 (PTP) is implemented to synchronize a real-time clock, and accuracy is less than 300 ns. We developed two types of observation node. One equips a pressure gauge for observation of tsunami-waves and vertical crustal deformation, and another has an external port for additional sensors using PoE. Deployment of the second system was carried out in September 2015 by using a commercial telecommunication cable ship. At completion of the deployment, the system started collecting data on seafloor immediately. The noise levels at the deployed system are comparable to those at the existing cabled system off Sanriku. Reflecting a low noise environment, many earthquakes were recorded clearly. From the pressure data, pressure measurement has a resolution of less than 1 hPa, which corresponds to a change of water height of less than 1 cm, and all the pressure gauges in the system have collected consistent tidal data. Tsunami-waves in November 2016, which were generated by an earthquake with magnitude of 7.4 off Fukushima were clearly observed by all pressure gauges in the system.

*J07-3-04
Joint Symposium / J07. Tracking the sea floor in motion

Seafloor deformation due to ocean tidal loading observed by seafloor cabled network.

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Seafloor observation hosted by seafloor cabled network such as DONET (Dense Ocean-Floor Network for Earthquake and Tsunamis) have potential to observe process of slow crustal deformation occurring at plate margin which in many cases situated in the seafloor. Observation in deep seafloor borehole have recently documented occurrence of slow slip events. Investigation of seafloor broadband seismic records in tidal frequency obtained from DONET observatories, was conducted to see if such events of may be observed in the seafloor. The broadband seismic records (from Guralp CMG3T) have flat velocity response < 360s and were corrected to obtain acceleration response in tidal frequencies between 2 days and 1 hour. The corrected acceleration response in vertical direction were consistent in most of DONET observatories, with estimated tidal gravity change by GOTIC2, indicating these broadband seismometers have good sensitivity to gravity change in tidal frequencies. The horizontal acceleration response, corresponds to tilting, on the other hand, showed differences between sites. The amplitude of diurnal tidal response varied between 0.1 – 2 microradians, significantly larger than those estimated for earth tide. The observed tidal tilt responses were at many sites in phase with seafloor pressure variation in both horizontal axes. This observation indicates significant effect of seafloor deformation due to ocean tide loading in these sites. The linearly correlating tilting were observed in may sites in accretionary prism of dipping subseafloor structure. It is considered that ocean tidal loading at such setting results in horizontal variation of deformation that was observed as the large amplitude tidal tilting. Therefore, seafloor tilt/strain measurement may be used to indicate slow crustal deformation, but with cautious estimate of the effect of ocean loading at each sites.

*J07-3-05
Joint Symposium / J07. Tracking the sea floor in motion

Monitoring submarine fault deformation using direct-path ranging

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The seafloor stores crucial information on sub-seafloor processes, including stress, elastic strain, and earthquakes. This information may be extracted through the nascent scientific field of seafloor geodesy. The GeoSEA (Geodetic Earthquake Observatory on the SEAfloor) array uses acoustic signals for direct-path ranging and relative positioning at mm-scale resolution for a period of up to 3.5 years. The transponders also include high-precision pressure sensors to monitor vertical movements and dual-axis inclinometers in order to measure their altitude as well as any change in submarine fault zones and characterizing their behavior (locked or aseismically creeping). A further component of the network is GeoSURF, a self-steering autonomous surface vehicle (Wave Glider), which monitors system health and is able to upload the seafloor data to the sea surface and to transfer it via satellite. Seafloor transponders are currently installed across a dextral strike-slip fault to measure the instability of the eastern flank of Mt Etna in Sicily, and along the North Anatolian Fault offshore Istanbul to measure the strain build-up along the fault in a seismic gap. In addition, three arrays are currently deployed on the marine forearc and outer rise of the North Chilean subduction zone system. This segment of the Nazca-South American plate boundary has last ruptured in an earthquake in 1877 and was identified as a seismic gap prior to the 2014 Iquique earthquake (Mw 8.1). The southern portion of the segment remains unbroken by a recent earthquake. The first 12 month of all geodetic installations were analyzed and we discuss baselines with precision less than 5 mm for ranges up to 2000 m of distance and compare them with synthetic baselines. In all three tectonic settings, the obtained baseline changes remain within the resolution limits. In the case of the North Anatolian Fault, this suggests a locked fault zone.

*J07-3-06
Joint Symposium / J07. Tracking the sea floor in motion

Slip rate of the North Anatolian Fault at the western part of the Sea of Marmara through seafloor geodetic measurement for two years

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The North Anatolian Fault (NAF) regionally has right-lateral block motion (~25 mm/yr) but local slip rate along the fault varies from place to place, which may control the inter-seismic stress accumulation. Rupture area along NAF is known to migrate roughly from east to west in the last century. The Marmara segment is known as seismic gap since 1766 (Marmara earthquake) or 1912 (Ganos earthquake / Murefte-Sarkoy earthquake), while the Izmit and Duzce earthquakes just east of the Marmara segment occurred in 1999. Thus, we investigate slip rate of NAF in the Sea of Marmara using seafloor acoustic extensometers, where on-shore geodetic observations (e.g. GNSS or InSAR) cannot be accessible.
In 2014, we installed four instruments at the Western High, where the Marmara main fault can be clearly identified, and added one more instrument in 2015. Since then, we recovered almost two years of continuous ranging data and evaluated the creep rate at this site as 10 +/- 5 mm/yr, which corresponds nearly a half coupling rate to the regional block motion. Using this constraint and surrounding onshore GNSS data, we constructed a simple fault model, that has partial creep layer from the seafloor to some 10-30 km depth and full creep below. We have installed two additional GNSS site in the Sea of Marmara since 2016 in order to constrain depth extent of the partial creep layer, which may be discussed with the seismicity distribution obtained by ongoing OBS surveys.
Acknowledgement: This observation is carried out in the MarDiM (Marmara Disaster Mitigation) project, SATREPS promoted by JICA, JST and Ministry of Development of Turkey

*J07-P-01
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Towards an Ocean Bottom Geodetic Observatory In Mexico: The First Steps

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Ocean bottom geodesy has proven important for observing static offsets occurring during large earthquakes (e.g. Sato et al 2011; Ito et al 2011; Kido et al 2011), to observe slow earthquakes (Ito et al 2013; Wallace et al., 2016), as well as slower tectonic motions (Chadwell & Spiess, 2008).

The Guerrero Seismic Gap, a one hundred kilometer segment of the Mexican subduction zone, has not experienced a large earthquake since at least 1911 (Singh et al 1981). Whether the zone is ripe for a new earthquake or not, depends on the amount of aseismic slip occurring on the fault plane in the inter seismic period, either as continuous creep or slow slip events. In the down-dip part of the segment, large (M˜7) slow slip events have been observed about every four years (e.g. Kostoglodov 2003, Larson et al 2006, Radiguet et al 2012). However, it is not clear to which degree the near trench area participates in these events. The Guerrero Gap is the closest segment of the subduction zone to Mexico City. A large event in this zone could cause severe damage to Mexico City and could generate a tsunami that could strongly impact Acapulco and neighboring regions.

As a collaboration between SATREPS/JICA in Japan, and UNAM and CONACyT in Mexico, a network of 2 GPS-Acoustic sites as well as 7 ocean bottom pressure recorders is planned offshore the Mexican coast, in the Guerrero Gap. A wave glider will be used to measure the position of the GPS-A sites. The installation of the first instruments is planned for June 2017. This presentation will detail the types of instruments that are planned and their distribution, the type of signals that we hope to collect as well as the plans for the future.

*J07-P-02
Joint Symposium / J07. Tracking the sea floor in motion

Quantitative evaluation of error sources for the GPS-A seafloor geodesy

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Seafloor geodetic observations using the GPS-Acoustic ranging combination technique (GPS-A) accomplished several monumental works in the fields of seismology and geodesy [e.g., Gagnon et al., 2005; Sato et al., 2011; Yokota et al., 2016]. In this technique, we observe using vessels on the sea around the seafloor acoustic mirror-type transponders. Seafloor absolute positions were determined using this acoustic data, the attitude data and the GPS data on the vessels. Although the GPS-A technique achieved establishment of the sophisticated seafloor observation network, an observation precision (1 σ = 2 - 3 cm: horizontal) remains lower than other geodetic observation techniques. The observation precision is affected mainly by three error sources. These are GPS errors, a measuring error between GPS and a bottomed acoustic transducer (T-D error), and an effect of ocean disturbances for undersea sound speed structures (SSS errors).
First, we performed a numerical simulation study to check reactions of a seafloor positioning analysis in several cases of the GPS errors and the T-D error. The obtained results suggested that the seafloor positioning in our present system is affected in 5 mm-scale (1 σ) by the GPS and T-D error sources. Therefore, the positioning is affected majorly by the SSS error sources. We have reduced this effect using analytical approaches in this decade. In that process, spatial and temporal changes and spatial biases of SSS were approximated as fields modelled using high-order temporal functions. We review our current analysis flow and evaluate effects of ocean disturbances quantitatively.

Acknowledgements: We thank the Geospatial Information Authority of Japan (GSI) for high-rate GPS data for kinematic GPS analysis, and for daily coordinates of the sites on the GSI website.

*J07-P-03
Joint Symposium / J07. Tracking the sea floor in motion

Recent seafloor movement in and around the rupture zone of the 2011 Tohoku-oki earthquake detected by GPS-Acoustic seafloor geodesy

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The Hydrographic and Oceanographic Department of Japan Coast Guard has been developing a system for precise seafloor geodetic positioning with the GPS-Acoustic combination technique and deploying seafloor observation sites on the landward slope of the major trenches around Japan, such as the Japan Trench and the Nankai Trough.

After the 2011 Tohoku-oki earthquake (M9.0), we directly measured huge coseismic seafloor displacements at seafloor sites just above the source region (Sato et al., 2011). These displacements were more than four times larger than those at any onshore GNSS station. It provided definitive evidence of huge coseismic deformation beneath the ocean.

We have repeatedly performed the GPS-A seafloor geodetic observation to monitor the postseismic movement in and around the rupture zone. In contrast to the coastal GNSS sites where trenchward-upward movements were reported, the offshore seafloor sites above the main rupture zone exhibit landward displacements with significant subsidence(Watanabe et al., 2014).

Although the terrestrial movements were reasonably interpreted by afterslip beneath the coastal area, the offshore results are rather consistent with effects predicted from viscoelastic relaxation in the upper mantle, providing definitive evidence of its occurrence.

In this presentation, we will report and discuss the most recent results of postseismic seafloor movement obtained after the paper by Watanabe et al., (2014).

Acknowledgements: We thank the Geospatial Information Authority of Japan (GSI) for high-rate GPS data for kinematic GPS analysis, and for daily coordinates of the sites on the GSI website.

Detection of offshore vertical displacements after the 2011 Tohoku-oki Earthquake using GPS/A observations

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After the 2011 Tohoku-oki Earthquake, GPS/Acoustic (GPS/A) observations have revealed extensive postseismic displacement pattern [Watanabe et al., 2014, GRL; Tomita et al., 2016, AGU], which provides strong constraints on modeling of the postsesimic deformation processes [e.g., Sun et al., 2014, Nature]. Most of the GPS/A observation results are limited in horizontal components because vertical component has large errors due to the trade-off nature with sound speed in the seawater. However, vertical motions are sensitive to postseismic processes; therefore, in this study, we challenge to estimate vertical displacements after the Tohoku Earthquake, from Sep. 2012 to Nov. 2016, at the 20 GPS/A sites located in the Tohoku-oki region.

In order to estimate vertical motions, numerous acoustic ranging data covering extensive sea-surface points are needed to distinguish the vertical motions and sound speed variation[Sato et al., 2013, J. Geod.]. Although, in our survey style, acoustic ranging was mainly performed at a fixed sea-surface point (the center of each transponder array) with the aim to focus on detecting the horizontal motions [e.g., Kido et al., 2006, EPS], we have also occasionally conducted moving surveys to collect acoustic ranging data covering the minimum extent above each transponder array. Using these data, we calculated displacement rates of the vertical motions.

The obtained vertical displacement rates show a spatially characterized pattern: subsidence above the coseismic rupture area and uplift near the trench, but they have 3-15 cm/yr errors in 1 σ that are much larger than the errors in the horizontal components. Due to the large errors, it is difficult to discuss the postseismic deformation processes at the moment. Nevertheless, this study successfully showed the potential capability of our data for detecting vertical motions. Further collection of data and appropriate evaluation of the errors will be required to obtain more accurate results.

*J07-P-05
Joint Symposium / J07. Tracking the sea floor in motion

Little evidence of shortening motion across the Japan Trench after the 2011 Tohoku-oki earthquake from direct-path acoustic ranging

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After the 2011 Tohoku-oki earthquake, large postseismic deformation in ocean has been detected by GPS/Acoustic observations both the landward and oceanward slope of the Japan trench, which mainly attributed to the viscoelastic relaxation induced by the mainshock (e.g. Sun et al., 2014, Nature; Watanabe et al., 2014, GRL; Tomita et al., 2015, GRL) especially in the large slip region (off-Miyagi). Crustal deformation near the trench axis play important role on a huge earthquake, whose rupture area extend to the trench. However, convergence rate just at the trench axis is not clear from GPS/A observation. Therefore, we have carried out seafloor acoustic direct-path ranging across the frontal wedge to reveal locking state.
Direct-path acoustic ranging measures two-way travel times between a pair of instruments installed on the seafloor continuously for more than one year and as precisely as ˜ 1 mm/yr for 1 km baseline. So far, we have completed three periods of observation, during 2013–2014, 2014–2015, and 2015–2016, in the region where significant coseismic slip was observed (e.g. Iinuma et al., 2012, JGR). In this paper, we show results of the long-term continuous observations from 2013 to 2016. All of results show little evidence of shortening motion across the trench after the Tohoku-oki earthquake.
Furthermore, we are planning to install another instrument in the Fukushima-oki region, where relatively large postseismic slip is expected (Sun and Wang, 2015, JGR) to reveal heterogeneous locking state. It will be planned to deploy in March 2017 and to recover in 2018. We expect that spatially heterogeneous convergency speed that will be caused by postseismic slip can be detected by this additional observation.
Acknowledgement: This observation is supported by JSPS KAKENHI (26000002). The installation and recovery of the instruments were executed during the KAIREI (KR15-15) and SHINSEIMARU (KS-16-14) cruises.

*J07-P-06
Joint Symposium / J07. Tracking the sea floor in motion

Characteristics of a quartz pressure sensor assuming an ocean bottom environment for highly accurate measurements of small and long-term crustal deformation

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In the Nankai Trough region, several large interplate earthquakes occurred repeatedly due to a subduction of the Philippine Sea Plate beneath the Eurasian Plate. In this area, Japan Agency for Marine-Earth Science and Technology (JAMSTEC) have deployed cabled observatory system (DONET) and long-term borehole monitoring systems (LTBMS) to monitor earthquakes and tsunamis, and to understand a seismogenic process of large interplate earthquakes. Seafloor pressure measurements are continuously conducted since the installation of the observatories, and are important for the detection of long-term crustal deformations to obtain geophysical knowledge associated with the occurrence of large earthquakes. However, pressure values contain instrumental drifts in the sensors in addition to the pressure changes associated with crustal deformations on the seafloor. Therefore calibrations of the pressure sensor is indispensable. We are developing a mobile pressure gauge to calibrate existing pressure sensor. The gauge has a quartz pressure sensor as a water pressure sensor. A target accuracy of the gauge is less than 1 hPa compared to the absolute pressure value to detect small crustal deformations. Machida et al. (2016) assessed a quartz pressure sensor characteristics assuming an ocean bottom environment in the laboratory. The results showed that several factors, such as a temperature hysteresis and a pressure hysteresis, cause less-accurate water pressure measurements. We conducted further assessments regarding attitude of the sensor. Results showed that the attitudes have an impact on the target accuracy. Based on the assessments, specifications of the gauge has to be designed to achieve the accurate water pressure measurements on the order of 1hPa. It would contribute to obtain long-term small amounts of seafloor displacements related to geophysical phenomena.

*J07-P-07
Joint Symposium / J07. Tracking the sea floor in motion

Investigation of long period behaviors of seafloor pressure records based on field data and laboratory test results

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Seafloor pressure monitoring is an effective mean to detect vertical crustal deformation in offshore areas. A small sensor of high precision and low power consumption enables to build an ocean bottom observation system to make continuous observations for one to two years. Several studies demonstrated that the bottom pressure monitoring can detect transient signals associated with tectonic events having time constants shorter than a month. However, it is difficult to detect tectonic events of much slower deformation rates due to lack of the knowledge about exact origins of longterm variations in the pressure records obtained at the seafloor. In this paper, we discuss about longterm characteristics of ocean bottom pressure records based on the actual data obtained by repeating deployment of free-fall/pop-up type instruments in the Japan Trench area as well as by laboratory experiments. A similar pattern of the temporal variation can often be identified on the seafloor records obtained by the identical pressure sensor. Previous laboratory experiments on the response of pressure sensors of the same kind showed a transient behavior after applying high pressure has several similarities to those on the seafloor observation records. These suggest that the sensor specific characteristics can be dominant in the field data and may be removed after estimating it through laboratory tests. Motivated by this idea, we are carrying out a laboratory experiment to clarify exact behavior of the pressure sensor previously used in the field observations. Another experiments are done to know stability of a counting clock for frequency measurement.

*J07-P-08
Joint Symposium / J07. Tracking the sea floor in motion

Reexamination of the fault model for transient slow slip event in the Japan Trench before the 2011 Tohoku-Oki earthquake

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Slow slip events are one of the important phenomena in the plate interface. Ito et al. (2013) investigated two transient slow slip events that occurred before the 2011 Tohoku-Oki earthquake deduced from the dense ocean bottom pressure (OBP) gauge data. They adopted differential pressure record between neighboring two OBPs for the effective removal of the remaining non-tidal oceanic mass variation. Their approach, however, can only know the relative displacement between two adjacent stations. Thus, it is difficult to understand the absolute displacement in each OBP station. Based on these background, we reexamined the SSE fault model using reprocessed OBP data set.
We used 8 OBP stations (TJT1, GJT3, P09, P08, P06, P02, P03, and P07) which is the almost same data set with Ito et al. (2013). The ocean tide and by non-tidal oceanic mass variation are removed by the model. We fitted the drift model (combination of an initial exponential and a linear component) to each of the observed time series to estimate the drift function of individual sensors. Even though the such procedure, the residual component still appeared. Thus, we calculated the differential time series of the OBPs in the eastern part (TJT1, GJT3, P09, and P08) relative to the averaged time series in the distant OBP stations (P06, P02, P03, and P07). Furthermore, we calculated the displacement field in each OBP station of eastern part according to the same definition of the time window with Ito et al. (2013).
We obtained the characteristic result between 19 Feb. to 8 March, 2011. TJT1 site, which located in the most eastern site, showed clear uplift. In contrast, GJT3 site, which is the neighboring site of the TJT1, shows small subsidence. Based on these data, we reexamined the SSE fault model. Obtained result shows the possibility of two fault locations. First model located in the very shallow part of the plate interface, the second model located in the slightly deeper part compared with the first one.

Changes in physical properties of the Nankai Trough megasplay fault induced by earthquakes, detected by continuous pressure monitoring

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One primary objective of Integrated Ocean Drilling Program (IODP) Expedition 365, conducted as part of the NanTroSEIZE project, was to recover a temporary observatory, termed the "GeniusPlug" to monitor formation, pore fluid pressure and temperature within a major splay fault that branches from the main plate interface, at a depth of ˜400 m below sea floor (mbsf). The instruments were installed in Dec. 2010 and recovered in April 2016, yielding 5.3 years record of formation pressure and temperature within fault zone. Here, we use the pressure timeseries, and in particular the response to ocean tidal loading, to evaluate changes in physical properties of fault zone induced by several regional earthquakes. To accomplish this, we quantify: (1) the amplitude of the formation's response to tidal loading, defined in terms of a tidal loading efficiency, governed primarily by the formation and fluid elastic properties; (2) the phase lag between the ocean tidal signal and the measured response in the observatory, which is governed by a combination of formation hydraulic diffusivity and the relative compressibilities of the formation and sensing volume; and (3) pressure steps associated with earthquakes, identified in formation pressure after removal of the tidal signal. We observe essentially no phase lag, but in for many events we detect both pressure steps and transient decreases in loading efficiency. To reveal the cause of these changes, we investigate the effects of static and dynamic crustal strains. Most of the detected changes represent pressure increases and loading efficiency decreases. We speculate that disruption of grain contacts and subsequent pore collapse induced by dynamic strain produces changes of hydraulic properties in the fault zone. Alternatively, these changes could reflect exsolution of gas from pore fluids that drives pore pressures up while simultaneously reducing loading efficiency by increasing the compressibility of pore filling fluids.

Possibility of tilt observation at the seafloor by a mobile ocean bottom seismometer

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Since 1999, we had developed the broadband ocean bottom seismometer (BBOBS) and its new generation (BBOBS-NX), and, with them, performed many practical observations to create a new category of the ocean bottom broadband seismology. High mobility of the BBOBS and BBOBS-NX can be a breakthrough to realize the geodetic observation network on the seafloor. Two kinds of attempts to expand observation range toward the geodetic one have been started since 2009. One is for detecting vertical displacement by attaching an absolute pressure gauge with the BBOBS, and another is for tilt observation by using the BBOBS or BBOBS-NX. In this presentation, we will report results for the later. The tilt is measured from two horizontal mass position (acceleration) signals as offsets from the level. The first test was performed at the land pit in 2010. The result was comparable to that of the water tube tilt-meter there, with resolution of better than a micro radian. Next, a practical observation at the seafloor off Boso was done as the feasibility study from April 2013 for one year. In January 2014, a slow slip event (SSE) occurred near the site. The tilt data was processed by removing for the mechanical relaxation and tides. The result shows clear peak started from the late Dec. 2013, but the tilt was not remained after the SSE ended. As the data length of one-year seemed short, two tilt observations are in operation by the BBOBS-NX since 2015, one is at the same site above and another is off Tohoku area, both for two years. Moreover, we made tilt observations by the BBOBS on the seafloor 4 times at 3 sites, 2 of 4 cases were with a current profiler. Compared with the tilt data by the BBOBS-NX using a penetrated sensor, the effective resolution is more than ten micro radian, which is similar to the horizontal noise difference due to the bottom current. But, the BBOBS is still useful to detect such oceanographic events as internal bores unstably generated along seafloor slopes.

*J07-P-11
Joint Symposium / J07. Tracking the sea floor in motion

Monitoring of the shallow tremors around the source areas of the Nankai and Tonankai earthquakes by ocean bottom observations

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Japan Agency for Marine-Earth Science and Technology (JAMSTEC) installed two ocean bottom observation systems in the source area of the Nankai and Tonankai earthquakes along the Nankai trough, southwest Japan (e.g., Kaneda et al, 2015; Kawaguchi et al., 2015; Kopf et al., 2011); one is the cabled observation system called Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET), the other is the borehole observation system called Long-Term Borehole Monitoring System (LTBMS). LTBMS and DONET stations have several kinds of the sensors such as a broadband seismometer, a quartz-type pressure gauge and a pore pressure gauge on and under the seafloor for the seismic and geodetic observations. The digitized data recorded at stations, which are distributed between coast and trough axis, are continuously transferred to our laboratory in real-time. By using these data, we can continuously monitor the tremors on the plate interface shallower than the source areas of the mega-thrust earthquakes along the Nankai trough at where the past studies have little detected tremors. In this study we purpose to monitor the non-volcanic tremors around the LTBMS and DONET stations, especially shallow ones.
By applying the envelope correlation method (Ide, 2010; Ide, 2012) to records of the broadband seismometers between Jan. 2011 and Dec. 2016, we tried to detect non-volcanic tremors around the source areas of the mega-thrust earthquakes. We detected both of the stable and episodic tremor activities. Tremors have stably occurred at the shallower part than the source area of the Tonankai earthquake, which almost corresponds to the aftershock area of the 2004 off Kii peninsula earthquake. Episodic tremors occurred either alone or with the large earthquakes (e.g., the off Mie earthquake on 1 Apr. 2016). Some long-term deviations of the pore pressure, which might indicate the slow slips, were detected at almost same time with the occurrences of the tremors.

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Site amplification at Nankai seafloor observation network DONET1 in Japan evaluated by spectral inversion

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Seafloor strong motion observation networks such as DONET and S-net have been deployed in the subduction zones of Japan. Their observations are expected to be useful for the real-time analyses on the magnitude estimation and the strong-motion forecast for subduction earthquakes. For these applications, site amplifications at the seafloor stations need to be evaluated because site amplifications caused by thick low-velocity sediments in the subduction zones can strongly affect the real-time analyses. In this study, we focus on DONET1, which are operated by NIED and JAMSTEC in the Nankai subduction zone, Japan, and evaluate their site amplification factors by the spectral inversion method.
We estimate site amplifications by separating source, propagation path, and site characteristics from observed Fourier amplitude spectra based on the spectral inversion technique (Iwata and Irikura 1986). The frequency band of this analysis is 0.2–10 Hz. We use the vector summation of two horizontal components of Fourier amplitude spectra, which are obtained from S-wave records of 20.48 s. The amplitude spectra are smoothed by the filter of Konno and Ohmachi (1999). We use records of strong motion seismographs at DONET1 and records of broadband seismograph at F-net of NIED. To solve a problem of trade-off between the source spectra and site effect, we assume the F-net KMT station as a reference rock site whose amplification factor is 2, following the procedure of Moya and Irikura (2000).
The spectral inversion indicates that all DONET1 stations, especially near-land stations (Nodes A and B) and near-trench stations (Node C), have larger site amplification factors than the reference station. The site amplification factors at the stations of Nodes A and B are ~10 in the broad frequency band (0.2–5 Hz). The site amplification factors at the stations of Node C have a sharp peak at ~5 Hz with the value of ~20.

*J08-1-01
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

3-D S-wave velocity structure under the Changbaishan volcanic area in Northeast China inverted with dense NECsaids array

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Previous studies show the prevalence of low velocities beneath the Changbaishan volcano, but debate continues about the details of the structure. We use data predominantly from our dense temporary NECsaids array (NorthEast China Seismic Array to Investigate Deep Subduction), but also incorporating data from surrounding permanent broadband seismic stations, to map Rayleigh-wave phase speeds in the crust and lithospheric mantle under the Changbaishan volcanic area in Northeast China. Then the Rayleigh wave phase velocity dispersions are inverted to determine 1-D shear wave velocity and assembled into 3-D model. The results show the S wave velocity structure of the crust has lateral and vertical heterogeneity, the velocity structure of shallow crust is well related with the tectonic units on the surface, and the deep structure reveals the volcanism and regional deep thermal erosion effect. The low velocity anomaly bodies are found in the crust and upper mantle beneath the Changbaishan volcano and have a tendency to extend to deeper, which may be the magma chamber in crust of the Changbaishan volcano. There is also a weak low velocity anomaly body in the middle-lower crust and upper mantle beneath the Longgang volcano, which may be related to the remains after its eruption.

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First insights into the deep structure of the eastern Australian passive margin using wide-angle seismic data: Crustal segmentation from the Tasman Basin to the northern Lord Howe Rise

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The eastern Australian margin was shaped by the fragmentation of eastern Gondwana during the Late Cretaceous. This led to the opening of the Tasman Basin and to the formation of sub-parallel ridges and basins, including the Lord Howe Rise. To image the deep structure of the region, a large-scale crustal experiment was conducted by JAMSTEC and Geoscience Australia onboard the R/V Kairei with the deployment of 100 ocean-bottom seismometers (OBS) along a 680 km profile at 27.2S. The OBSs register clear refracted arrivals from the crust and the mantle that are recorded at very large offsets, as great as 300 km. Both pre- and post-critical reflected phases from the Moho (PmP) are also very clearly recorded by the OBSs. We performed first-arrival tomographic inversion to analyze the data. An initial layered P-wave velocity model was built using the two-way travel time reflection from the basement interpreted from coincident multi-channel seismic data to constrain the thickness of the sedimentary layer. During the inversion, the PmP arrivals are used to add constraints on the thickness of the crust. The uncertainty in the final P-wave velocity model is tested by applying Monte Carlo analysis. The final Vp model shows large variations in crustal thickness and allows the identification of distinct crustal domains along the profile from the Tasman Basin to the northern Lord Howe Rise: the Tasman Basin is an oceanic domain with ~7km thick crust; further east, a 15km crust is present below the Dampier Ridge; the crust again thins to 8km below the Middleton Basin; and the northern Lord Howe Rise is floored by a 21km thick crust. Further work will compare the modeled P-wave velocities with previously published results from the southwest Pacific region and other well-known tectonic provinces from around the world to discuss the variation of nature of the crust along the profile. This will help to better understand the processes that led to the fragmentation of eastern Gondwana.

*J08-1-03
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Formation of the Lord Howe Rise continental ribbon during eastern Gondwana breakup from multi-channel seismic reflection data

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The Lord Howe Rise continental ribbon, offshore eastern Australia, formed during the Late Cretaceous rifting of eastern Gondwana. This project focuses on multi-channel seismic reflection and bathymetry data collected on a multi-leg marine geophysical survey in 2016 to constrain the nature of rifting and the formation of the Lord Howe Rise. We present processed pre-stack depth-migrated seismic reflection images and interpretations of a regional, ~900 km long east–west-oriented profile at 27.2S, from the oceanic Tasman Basin to the extended continental crust of the Lord Howe Rise. We find that the Tasman Basin contains buried basins that may be related to early transform faulting. The Tasman Basin has a sharp eastern boundary against the Dampier Ridge, within which are multiple rift basins up to 3 km deep. These basins are similar to those found on the Lord Howe Rise. The Middleton Basin separates the Dampier Ridge and the Lord Howe Rise and is a broad, well-stratified sedimentary basin of up to ~3.5 km thickness. This basin contains an unconformity that separates deeper sediments, likely deposited during rifting of the Dampier Ridge, that are conformable with the basement and younger strata that filled the basin post-rifting. Both syn-rift and post-rift sedimentary sequences are found on the Lord Howe Rise. To better understand these rifting events, we present grids of pre-stack time-migrated seismic reflection lines covering two rift basins of the Lord Howe Rise. The two basins show contrasting evolution, including variations in normal faulting intensity within the syn-rift sequences. These results help constrain the dynamic processes that caused the formation of the Lord Howe Rise continental ribbon.

*J08-1-04

Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Coupled anisotropic and isotropic body-wave tomography of the upper mantle beneath northern Fennoscandia - Application of a novel code AniTomo to data from passive seismic experiment LAPNET (Finland)

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Seismological investigations of continental mantle lithosphere, particularly of its anisotropic structure, advance our understanding of plate tectonics and formation of continents. Orientation of anisotropic fabrics reflects stress fields during the lithosphere origin and its later deformations. To contribute to studies of large-scale upper-mantle structures, we have developed novel code AniTomo for regional anisotropic tomography. AniTomo allows a simultaneous inversion of relative travel-time residuals of teleseismic P waves both for 3D distribution of isotropic-velocity perturbations and anisotropy in the upper mantle. Weak hexagonal anisotropy with symmetry axes oriented generally in 3D is assumed. The novel code was successfully tested on large series of synthetic datasets and synthetic structures. In this contribution we present results of the first application of AniTomo to data from passive seismic experiment LAPNET (northern Fennoscandia, 2007 - 2009). This Precambrian region is tectonically stable and has a thick anisotropic mantle lithosphere (Plomerova and Babuska, Lithos 2010) without significant thermal heterogeneities. The strongest anisotropy and the largest velocity perturbations concentrate in the mantle-lithospheric part of the tomographic model down to 170km. Regions with laterally and vertically consistent anisotropy can be delimitted there. The anisotropic regions from the tomography correspond to domains of consistent fabric derived from variations of P- and SKS-wave anisotropic parameters (Plomerova et al., SE 2011). Particularly, the western part of the model exhibits a distinct and uniform fabric sharply separated from the surroundings. The eastern boundary of this region gradually shifts westward with increasing depth. We connect the retrieved domain-like anisotropic structure of the mantle lithosphere in the northern Fennoscandia with preserved fossil fabrics of the Archean micro-plates, accreted during the Precambrian orogenic processes.

*J08-1-05
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Waveform-based estimation of velocity heterogeneity for prestack imaging from multifold wide-aperture seismic data

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Deep seismic reflection profiling with rugged acquisition topography, crookedness of seismic lines has been imposed serious restrictions and compromises on both data processing and acquisition. In addition to complex subsurface structure, irregular distribution of shots, and large noise level of surface wave and back-scattered wave often result in deterioration of the data quality and poor reflection image in seismic profile. In recent years, the quest for increased precision and channel capacity of receiver system led to the combination of telemetry and autonomous recorders with the deployment of dense seismic array for deep seismic profiling in Japan. For deep seismic profiling with wide-aperture geometry, dense spatial sampling and low-frequency bandwidth, velocity structures estimated through turning-ray tomography (TRT) are restricted in resolution, since TRT depends on direct arrivals of seismic wave with the assumption of asymptotic ray theory. On the other hand, full waveform inversion (FWI) based on full wavefield modeling and inversion has an advantage to estimate high-resolution velocity heterogeneity. In our study, the hybrid velocity estimation of TRT, FWI and reflection velocity analysis by PSDM (Prestack Depth Migration) was applied to onshore-offshore integrated deep seismic data across Niigata basin, central Japan. The uncertainty of the tomography solutions was evaluated using a nonlinear Monte Carlo approach with randomized initial models, and the velocity structure of deep basin structure is constrained by subsequent forward reflection and refraction modeling. The combination of PSDM-driven velocity analysis and FWI was confirmed to have the potential imaging capabilities for improved prestack depth migration. Main features of basin development, such as early Miocene normal faulting, associated with the formation of Japan Sea, and shortening deformation since Pliocene, are well demonstrated on the final seismic sections.

*J08-1-06
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Seismic Imagings of Sub-Crustal Reflectors Beneath the Iberia Microplate

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Deep upper mantle seismic scattering features have been imaged beneath the Iberia microplate. Normal incidence and wide-angle seismic reflection experiments in the area: ILIHA, IBERSEIS, and ALCUDIA, provide seismic constraints on these sub-crustal structures. Mantle reflectors were identified on the IBERSEIS wide angle shot records at offsets of 180 km. These correspond to an interpreted boundary located at 61-72 km depth with a Vp increase from 8.2 km/s to 8.3 km/s. This layer was interpreted to be characterized by a Vp gradient because the reflector was not identified in the coincident vertical incidence dataset. The ‘Hales gradient zone', i.e. the boundary between spinel and garnet peridotites, was the preferred interpretation. The ALCUDIA experiment also imaged prominent sub-crustal arrivals with similar characteristics. However, these reflections also appear, locally and at 19 s TWT, in the vertical incidence stack. In addition, the ALCUDIA wide-angle dataset show deeper reflectors that maybe, preliminarily, associated to mantle anisotropy fabrics or even with the lithosphere-asthenosphere boundary. Both upper mantle reflectors are modeled at 65 km and 100 km depth, respectively, shallowing to the north to 55 km and 90 km depth. Integration of the information provided by the IBERSEIS and ALCUDIA datasets with older and lower resolution data from the ILIHA project, where three sub-crustal phases were identified in SW Iberia, indicates that, in this area, mantle reflectivity is outstanding. Also, modeling of all the datasets contributes to map, at a regional scale, the Hales discontinuity or gradient zone in southwest Iberia.
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*J08-2-01
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Tomographic imaging of the seismic velocity structure in southern Hokkaido, Japan: Implications for distributions of the crustal deep low-frequency earthquakes

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At southern Hokkaido, Japan, the crustal deep low-frequency earthquakes (CDLFE) are often observed beneath both active volcanoes and non-active volcanic area, which corresponds to shallow swarm-like activity of the regular crustal earthquakes. It is considered that the CDLFEs relate to activity of volcanoes and regular crustal earthquakes (e.g., Takahashi and Miyamura, 2009). However, those relations have not been revealed in clearly. In order to improve understandings for the CDLFEs and those relating phenomena, we investigated seismic velocity structure beneath southern Hokkaido and discussed the relations based on the heterogeneous structure.

For estimating the seismic velocity structure in detailed, we adapted the double-difference tomography method (Zhang and Thurber, 2003; 2006). The number of earthquakes occurred in southern Hokkaido in the period from March 2003 to June 2016 were 15,645 (A magnitude range of 1.5-6.5), and travel times of 306,335 for P wave and 242,093 for S wave were adapted to the estimations.

The obtained results obviously show that the low-velocity and high-Vp/Vs zones are estimated in depths of about 20-40 km beneath active volcanoes. Moreover, it is confirmed extensions of the low-velocity and high-Vp/Vs zones to the CDLFEs within the non-active volcanic area. At a depth of 10 km, seismic velocity beneath the volcanoes tends to be decreased from that calculated in surroundings while high-velocity anomaly is widely detected. The crustal earthquakes involving swarm-like activity above the CDLFEs are correspondingly located with the high-velocity zones. Because it is considered that presence and migration of fluids or melts contribute to trigger the CDLFEs (e.g., Ukawa and Ohtake, 1987), these observations suggests that the CDLFEs closely relates to the crustal earthquakes and volcanoes though the fluids or melts, and the related phenomena may be linked to the crustal heterogeneity.

*J08-2-02
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Structural heterogeneities around inland earthquake areas in Hokkaido Island based on magnetotelluric observations

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Hokkaido Island, northern Japan is suited on the arc-arc boundary between the NE Japan and Kurile arcs. In the south part of the boundary zone, colliding structure is clearly recognized in the south part of the Island (Hidaka mountain range) but not in the north part. However, fold-and-thrust structures are distributed through the western margin of the arc-arc boundary. The north part of the fold-and-thrust zone is converging to the strain concentration zone in the eastern margin of Japan sea. In order to investigate the relationship between earthquakes and structural heterogeneity including deep area beneath earthquake zone, we conducted magnetotelluric measurements and modeled electrical resistivity distribution in the south part of Hidaka mountain range (Erimo area, Ichiara et al., 2016), south part of the fault-and-thrust zone (Ishikari-Toen fault zone, Yamaya et al., in press) and north part of the fault-and-thrust zone (Rumoi and Dohoku area, Ichihara et al., 2008, 2016).
In these areas, resistivity distributions reflect geological structure; thickness of the surface conductive zone is corresponding to that of sediment layer associated with fold-and-thrust activities. They indicate that MT survey is useful to investigate fold-and-thrust structure. A deep conductive areas were also revealed along the Hidaka main thrust and beneath the Ishikari-Toen fault zone and. They imply ductile zone affecting the strain concentration.

*J08-2-03
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Structure of the incoming/subducting Pacific Plate in the central part of the Japan Trench: Results from repeated ocean bottom seismograph observations

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Oceanic plate subduction is an important process to transport the water from the Earth's surface into the mantle. Recent active seismic surveys present that systematic reduction of the seismic velocities within oceanic crust and the uppermost mantle of incoming oceanic plate with the approach toward the trench. These seismic velocity changes are considered as a result of the oceanic plate hydration/alteration in the trench-outer rise region. However the active seismic studies can resolve the structure at depths down to a few km below the oceanic Moho. After the 2011 Tohoku-Oki earthquake, seismicity within the incoming/subducting Pacific plate in the trench-outer rise region of the Japan Trench is very active. Ocean bottom seismograph (OBS) observations have been conducted repeatedly in the trench-outer rise region of the central part of the Japan Trench since 2011. The active seismicity would give a chance to obtain structure information of the oceanic lithosphere based on the passive earthquake observations. We investigated seismic velocity structure through the travel time tomography by using the passive OBS observation data consisting of 120 stations and more than 8000 events in total. The results show that the seismic velocities within the oceanic mantle seaward of the Japan Trench reduce toward the trench axis. The reduction of the P-wave velocities, which may relate to the hydration/alteration of the oceanic plate, extended down to a depth of about 20 km below the oceanic Moho. We also investigated anisotropy and Q structures by using the OBS data. We will discuss the structures of the incoming Pacific plate and its hydration/alteration in the trench-outer rise region by combining the results from these analyses.

*J08-2-04

Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Seismic structure around the slow slip source in the northeastern Japan forearc by an airgun-ocean bottom seismometer survey

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Various kinds of slips have been observed along the plate boundary (PB) in the Japan Trench subduction zone; slow slip events (SSEs) happened in 2008 and 2011 at 37.7–38.7N in the source area of the 2011 Tohoku-oki earthquake. Faults hosting SSEs are often characterized by low seismic velocity anomalies. Although it is expected that the distribution of the interplate low velocity material can be identified by strong seismic reflectivity of the interface, a detail structure in the SSE source area remains unknown. To clarify seismic structure near the PB source, which will improve understanding of the mechanism of SSE generation, we made an airgun-OBS (Ocean Bottom Seismometer) survey in 2014. Survey lines covered the SSE source area in their southern sections.

The P-wave velocity (Vp) model estimated by a first arrival traveltime tomography (Fujie et al., 2013) showed distinct lateral Vp variation in the overriding plate; the high Vp (> ˜ 4 km/s) island arc upper crust (IUC) material was estimated to the south of 39 N, whereas the low Vp (< ˜ 3 km/s) unconsolidated sediment (US) distributed in the northern part of the survey line. A reflection traveltime mapping method (Fujie et al., 2006) imaged the PB as a continuous reflector at depths from 8 km to 14 km, where Vp is ˜ 5 km/s. The PB is more reflective beneath the IUC than that beneath the US. Since the Vp contrast between the IUC and the oceanic layer 2 may be small, the clear reflections from the PB suggest the existence of a low Vp channel layer along the PB. The spatial extent of high-Vp overriding crust and the highly reflective PB, identified to the south of 39N, almost coincides with the SSE source location. Therefore, our survey results suggest that the SSE source area is characterized by the presence of low-Vp channel layer along the PB beneath the high Vp overriding crust.

*J08-2-05
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Structural variation in the rupture zone of the 2011 Tohoku-oki earthquake and its implications for depth-dependent seismic-slip behaviors

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Seismological data of the 2011 Tohoku-oki earthquake (Mw 9.0) have revealed a clear depth-dependent variation in the source location between high- and low-frequency seismic energy radiation. However, structural variation, which may control seismic energy radiation, in the rupture zone have not been well studied. In this study, we therefore examined depth-varying structural characteristics by using seismic reflection data acquired along five profiles in the rupture zone. The resultant seismic images are characterized as a low-velocity frontal prism, a reflective zone at the trenchward tip of the continental block, and subducted horst-and-graben structures. The frontal prism is imaged as a low-velocity (Vp 2.0–3.5 km/s) wedge-shaped unit north of 37.5N, and abruptly transforms to a channel-like sedimentary unit south of 37.5N. Compiling the distribution of the frontal prism and the fault slip of the 2011 earthquake and the 1896 Sanriku earthquake, which is well-known as a tsunami earthquake, suggests that the coseismic slip to the trench may have occurred where the frontal prisms well developed. In 30 to 80 km landward from the trench, reflective zones with thickness of ~ 5 km were imaged at the base of the overriding block just above the subducted oceanic basement. Growth of subducted horst-and-graben structures (the throws of the normal faults associated with the horst-and-graben are larger by up to ~2 km) is imaged beneath the reflective zone. By comparing the seismic images and seismicity, we conclude that 1) in the area where a well-developed low-velocity frontal prism is imaged, seismicity along the plate interface is very low but the aftershocks of the 2011 earthquake occurred within the uppermost mantle and in the overriding plate, 2) in the area where growth of the subducted horst-and-graben structures are imaged, low levels of short-period seismic energy during the Tohoku-oki and weak background seismicity along the plate interface are observed.

*J08-2-06
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Investigation of seismicity and subsurface structure around northern Tohoku using seismic data recorded by AS-net

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From 2013 to 2014, we have installed a permanent local high-sensitivity seismic observation network, AS-net, at northern Tohoku and southwestern Hokkaido, Japan, for the purpose of monitoring earthquake activity and investigation of subsurface structure. AS-net covers the area where the other seismic stations are relatively sparse, and enhances the earthquake detection capability and provides dense continuous seismic data. The region is located on the Japan island arc containing fore-arc, back-arc showing relatively higher seismicity in Japan. In this presentation, we report the seismic activity and subsurface structure around northern Tohoku containing Aomori prefecture and southwestern Hokkaido investigated using data derived by AS-net and other stations.
We are making an original local earthquake catalogue for northern Tohoku from 2014 using data from 134 stations including 36 stations of AS-net. 11191 events were detected automatically using data from January 2014 to June 2016. By manual check of these events, 5961 earthquakes were determined. 4535 earthquakes were occurred in the crust (H <50 km), and the other were occurred at the upper boundary and the inside of Pacific plate. Some low-frequency events also occurred at some volcanic and non-volcanic regions (H <40 km). Above these low-frequency events, shallow normal earthquakes also occur actively. For crustal earthquakes (H <50 km), we could detect 2.5 times as many earthquakes as JMA hypocenter catalogue (1752 events). The site corrections for P and S arrival estimated using the difference between manual pick and theoretical travel time are considered in this hypocentral location. The site correction values differ depending on subregions reflecting their local site conditions. We also conduct seismic tomography using manual phase pick values for hypocentral location. We show the relationship between hypocentral distribution and the subsurface structure shown by the seismic tomography.

Failed rift system in northern Honshu, Japan, imaged by improved seismic velocity structure using offshore earthquake events

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We investigate the 3D seismic velocity structure beneath the ocean using offshore events with seismic tomographic method. Offshore events have a large uncertainty for focal depth determined by NIED Hi-net, however, NIED F-net determined the focal depth with moment tensor inversion. In this study, the data is the combination of the hypocenter catalog by NIED F-net and pick data by NIED Hi-net for offshore events as well as the hypocenter catalog and pick data by NIED Hi-net for events within the seismic network.
The target region, 20–48N and 120–148E, covers the Japanese Islands. The available data for use in the seismic tomography are manually picked 4693781 P-wave and 2342621 S-wave arrival times for 796779 earthquakes recorded at approximately 1300 stations from October 2000 to December 2014. The inversion reduces the RMS of the P-wave traveltime residual from 0.507 s to 0.193 s and that of the S-wave data from 0.609 s to 0.238 s after eight iterations.
Our new analysis clarified the failed rift structures, marked by higher Vp at lower crust and lower Vp at the upper crust, along the Japan Sea cost of central Honshu. Judging from the age of the rift basin, they were produced during the formation of the Japan Sea. Similar, rift structure also detected along the Pacific coast of Northern Honshu, it is marked by uplifted Moho surface, trending NS to NNW-SSE direction. Geologically, it is interpreted as a rift structure formed in the late Mesozoic. Further tectonic investigation for this probable Mesozoic rift is needed. These failed rift zones show similar features in seismic velocity structure and have shallow Moho (Matsubara et al., 2017).

Reference:
Matsubara M., H. Sato, T. Ishiyama, and A. D. Van Horne (2017) Configuration of the Moho discontinuity beneath the Japanese Islands derived from three-dimensional seismic tomography, Tectonophysics, in press, doi:10.1016/j.tecto.2016.11.025.

*J08-3-02
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Geometry and spatial variations of seismic reflection intensity of the upper surface of the Philippine Sea plate off the Boso Peninsula, Japan

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In the region off the Boso Peninsula (BP), Japan, the Pacific plate is subducting westward beneath both the Honshu island arc (HIA) and Philippine Sea plate (PHS), while the PHS is subducting northwestward under the HIA. These complex tectonic interactions have caused numerous seismic events such as the Boso Slow Slip Events (SSEs). To better understand these seismic events, it is important to determine the structure in this region.
Although some seismic surveys have been conducted off the BP, still further work is needed for farther offshore. We conducted a marine seismic experiment off the BP, from July to August 2009. Airgun shooting was conducted along 4 survey lines, and 27 Ocean Bottom Seismometers (OBSs) in total were deployed. We estimated 2-D and 3-D P-wave velocity structure from the airgun data using the PMDM (Progressive Model Development Method; Sato and Kenett, 2000) and the FAST (Zelt and Barton, 1998). Within our survey data, we recognized numerous reflections and estimated its depth by conducting the Traveltime mapping method (Fujie et al. 2006) (TTMAP) in both the on-line area and off-line area.
From the 2-D velocity model, we found that the dip of the upper surface of the PHS is shallow far off the BP. The TTMAP results in the 2-D models indicate that an area of high reflection intensity corresponds to the main slip area of the Boso SSEs. The TTMAP in the 3-D model is still under analysis.
Acknowledgement
The marine seismic experiment was conducted by R/V Hakuhou-maru of Japan Agency for Marine-Earth Science and Technology, and the OBSs were retrieved by Shincho-maru of Fukada salvage co. Ltd..We would like to thank captains and the crew of Hakuho-maru and Shincho-maru. This study was supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under its Observation and Research Program for Prediction of Earthquakes and Volcanic Eruptions, and from the Grants in Aid for Scientific Research (25287109).

*J08-3-03
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Hydrocarbon accumulation controlled by tectonic activity in the subduction zone: Insight from advanced seismic velocity analysis

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The presence of gas hydrates is widespread in the Kumano Forearc Basin which is situated above the Nankai accretionary prism off the Kii peninsula, Japan. Bottom-Simulating Reflectors (BSR) at the base of the gas hydrate stability zones has imaged as strong acoustic impedance contrast on the seismic profiles. When we applied seismic velocity analysis to 3D seismic data via automatic velocity picking, the results reveal the high velocity anomaly zone (1900-2500 m/sec) above BSR interpreted as Gas hydrate bearing sediments, and the low velocity anomaly zone (1300-2000 m/sec) beneath BSR interpreted as free gas bearing sediments. Based on the results, we suggest that the gas hydrates accumulated due to the free gas influx which migrated upward through the steeply dipping strata and faults or fractures cutting through the basin. The gas (or hydrate) accumulated area is further controlled by the large faults in the accretionary prism. Therefore these factors generated by intensive tectonic movements control the distribution and saturation pattern of gas hydrate and free gas formation. When we characterize the features of gas hydrate (i.e., double BSR caused by variation in temperature and pressure), we could discuss the history of tectonic and seismic activity in the accretionary prism.

Key words: gas hydrates, seismic velocity analysis, automatic velocity picking, free gas influx

*J08-3-04
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Imaging of the subducted Philippine Sea plate and the overriding SW Japan arc - Reinterpretation of the wide-angle reflection data in the Kii Peninsula, SW Japan -

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Our recent reinterpretation for seismic refraction/wide-angle reflection data in eastern Kii Peninsula, SW Japan, provided new structural information on the subducted Philippine Sea (PHS) plate and overriding the SW Japan arc.
The Kii peninsula is located in the eastern part of the well-known seismogenic zone along the Nankai trough. The plate boundary beneath this peninsula is in the stable or conditionally stable regime except for its southernmost tip (the northwestern end of the rupture area at the 1944 Tonankai earthquake (M7.9)). Our data were acquired in 2006 along 80-km line almost perpendicular to the Nankai trough. To image the structure of overriding the SW Japan arc, we retrieved virtual shot records from free-surface backscattered waves by the deconvolution interferometry. The subsequent CRS (Common Reflection Surface)/MDRS (Multi-Dip Reflection Surfaces) methods delineated a northward dipping reflector band just south of the Median Tectonic Line (MTL). This reflection band, about 10-15 km thick, includes the High-P Sambagawa Metamorphic belt, extending from 2-10 km to 25-35 km depth. The MTL itself is recognized as the uppermost part of this band inclining northward to a depth of nearly 25 km.
The PHS plate is well imaged as northward dipping reflectors in a depth range of 20-35 km beneath the southern half of our profile both by seismic refraction and reflection analyses. A thin (less than 1 km) low velocity (3.5~5km/s) layer is situated at the top of the PHS plate under the southernmost part of the profile, namely the trenchward half of the conditionally stable zone. In the central part of the profile (the landward half of the conditionally stable zone), strong reflectors with 2-3 km/s velocity contrast are distributed in a diffused manner at 30-35 km depths, around which low frequency earthquakes are occurring. The obtained lateral structural change is probably controlled by dehydrated fluids from the subducted PHS plate.

*J08-3-05
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Three dimensional attenuation structure in and around the source region of low frequency earthquakes beneath the Kii Peninsula, southwest Japan, revealed by dense seismic array observation

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Non-volcanic deep low frequency earthquakes (DLFE) have occurred along the isodepth contour of 30 to 40km of the subducting Philippine Sea plate (PSP) beneath the Kii Peninsula, southwest Japan. The DLFE's activity is not uniform and some clusters align from the WWS to the EEN of Kii Peninsula. Further seismicity of local earthquakes which occur around the PSP's Moho in the eastern part of the Kii Peninsula is lower than that of western part. To clarify the physical property which controls the seismicity of DLFEs and local earthquakes, we applied a combined inversion method to P wave spectra and obtained an attenuation (Q) structure there. Adding to routine seismic network's data, we used seismic waveforms recorded in three dense seismic array observation which were settled in perpendicular or parallel direction to DLFE clusters' alignment. Since length of the arrays reach approximately 90km (or 60km) with 1km station interval, it made us possible to estimate a detailed Q structure along the arrays.
Derived Qp images show that patch-like high Qp zones were distributed in the region just around the depth from 30 to 40km at the western part of the Kii Peninsula. These high Qp regions coincide with the regions where the DLFE clusters exist. On the contrary, we can find a low Qp zone at the same depth range in which high activity of the DLFEs is seen in the eastern part of the Kii Peninsula. This low Qp zone corresponds to the lower Vp and high Vp/Vs region derived from travel time tomography. Low Vp and high Vp/Vs generally suggest the existence of fluid and similar low Vp and high Vp/Vs region were found at the DLFE cluster of the western side. Then these results suggest the occurrence of the DLFEs may be associated with fluids dehydrated from the PSP, but its activity might be affected by different physical properties in both sides of the Kii Peninsula.

*J08-3-06
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Imaging the distribution of transient viscosity following the 2016 Mw 7.1 Kumamoto earthquake

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Postseismic studies of geodetic data following large earthquakes indicate a wide range of mechanisms contribute to the observed deformation and stress relaxation. Both on-fault afterslip and off-fault viscoelastic relaxation can contribute to the postseismic transient phase of the earthquake cycle. One problem with these (quasi-) dynamic models is that there is a wide range of parameter space to be investigated, with each parameter pair possessing their own tradeoffs. This becomes especially problematic when trying to model both on-fault and off-fault deformation simultaneously. Here, we draw insight from postseismic geodetic observations following the 2016 Mw 7.0 Kumamoto earthquake by utilizing a novel inversion technique.

We present a novel approach to invert for on-fault and off-fault deformation simultaneously using analytical Green's functions for distributed deformation at depth [Barbot, Moore and Lambert., 2016] and on-fault deformation [Okada 1992, Nikkhoo and Walter 2015]. Using these Green's functions, we jointly invert InSAR images and GEONET GPS time series following the Kumamoto earthquakes for afterslip and lower-crustal viscoelastic flow.

The calculated strain-rates in the lower crust are directly converted to effective viscosities and we investigate the implications of the effective viscosity structure within an outlier-senstitive Bayesian statistical framework to estimate in-situ parameters, such as temperature. Using our new method, we are able to interrogate the transient deformation in the first few months of the postseismic deformation to obtain these parameters.

The postseismic deformation at Kumamoto brings new insights into the distribution of brittle and ductile crustal processes beneath Japan and can be used to infer lower crustal properties.

*J08-P-01
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Multicore parallelization of 3D ray tracing algorithm using OpenMP

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Parallel computing is now being used to solve problems much faster than the traditional serial computations in a wide variety of scientific computing applications. Parallel programing allows us to break a problem into a discrete series and execute by different processing units simultaneously. Multi-core processors which support parallel computing are quite common now, however writing a parallel code is more difficult than a sequential code. OpenMP is a standard programming interface for shared memory parallel computing which helps to create more easily multithreaded codes of existing serial programs. In this work, we present the use of OpenMP to parallelize the Lotos bending algorithm (Koulakov, 2009) for ray tracing in a 3D velocity model. In order to take the advantage of multicore capabilities, the parallelization of the bending ray tracing was carried out for both data-parallel and task-parallel. We successfully achieved performance of the parallelized algorithm on two multicore laptops; intel i7 and intel i5.

*J08-P-02
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Waveform inversion to image laterally inhomogeneous crustal structure - comparison among waveform inversion, traveltime inversion, and seismic migration -

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High-resolution seismic velocity structure in geologically complex areas is of crucial importance for the understanding of evolution and formation processes associated with plate tectonics. However, it was difficult to image laterally inhomogeneous structural features such as sub-vertical intrusions into the crust by seismic migration of multi-channel seismic reflection (MCS) data or by traveltime analysis of ocean bottom seismographs (OBSs) using controlled sources. On one hand, migration has difficulties for imaging steep reflectors and, on the other hand, the spatial resolution of the traveltime analysis is low, especially when considering first-arrivals. Alternatively, full waveform inversion (FWI) is a promizing technique for an improved quantitative detailed seismic structure even in geologically complex area because full wave propagation is performed for honoring recorded traces.
In the fore-arc region of the Izu-Bonin island arc, Tatsumi and Stern (2006) suggested a sub-vertical intrusion of the middle crust below the Eocene paleo arc. For assessing the existence of such intrusive structural feature, we conducted MCS survey and wide-angle OBS-airgun survey (OBS deployed 1 km interval) in this region (Yamashita et al., 2009). We applied pre-stack depth migration to the MCS data, but we could not image the intrusive feature. On the contrary, we attempted to apply FWI to this wide-angle OBSs dataset and we succeeded in imaging this intrusive feature. From these results, we may deduce that the FWI is an effective tool for detecting steep tectonic structures such as sub-vertical intrusion.

*J08-P-03
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Feasibility of the waveform analysis to the existing conventional wide-angle seismic survey data - Ocean Bottom Seismometer (OBS) and controlled-source seismic surveys in the Nankai subduction zone -

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The OBS and controlled-source seismic survey is a powerful tool for imaging crustal structure beneath the seafloor. Conventionally, these data have been processed by traveltime analysis methods like a traveltime inversion, which provides us a large-scale crustal structure valuable for understanding the geodynamical processes oaccurring in the lithosphere.

In the traveltime analysis, we use arrival times only and do not utilize amplitude and phase. Therefore, if we could utilize the observed seismic waveform itself, we could extract more subseafloor information from the OBS survey data and might be able to image more detailed crustal structure.

Recently, new analysis methods utilizing the observed waveform, such as seismic interferometry, mirror imaging, and waveform inversion, have come into practical use. These modern waveform analysis methods enables us to image more detailed crustal structure than the conventional travletime analysis methods. However, to receive full benefits from these modern methods, we need to design seismic surveys to be optimal for waveform analysis, meaning dense OBS spacing.

To investigate the efficacy of the waveform analysis method for the existing conventional, actual OBS survey data, we applied these modern methods to a large number of OBS survey data obtained in the Nankai Trough subduction zone. These existing surveys were basically designed for travel-time analysis and OBS spacings were sparse (mostly 5 km). In addition, the data quality was not necessarily high because of narrow dynamic range of instruments. Despite these adverse conditions, we confirmed that these modern methods have a potential to extract detailed structural information, especially for the shallower part, from the existing sparse OBS survey data. In this talk, we are going to discuss the benefits and limitations of these waveform analysis methods to the conventional sparse OBS survey data.

*J08-P-04
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Inversion of Gravity Anomalies Using Primal-Dual Interior Point Methods

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Structural inversion of gravity datasets based on the use of density anomalies to derive robust images of the subsurface (delineating lithology and their boundaries) constitutes a fundamental non-invasive tool for geological exploration. The use of gravity data to estimate and interpret the substructure based on its density properties have proven efficient; however, the inherent non-uniqueness associated with most non-seismic geophysical datasets make this the ideal scenario for the use of recently developed robust constrained optimization techniques. We present a constrained optimization approach for a least squares inversion problem to characterize 2-Dimensional Earth density structure models based on gravity anomalies. The formulation inverts Bouguer gravity anomalies using polygons along with Primal-Dual Interior-Point methods for the optimization of the results, which include equality and inequality physical and structural constraints. We validate our results using synthetic density crustal structure models with varying complexity and illustrate the behavior of the algorithm using different initial density structure models and increasing noise levels in the observations. Moreover, we apply the approach to the Southern Rio Grande Rift (SRGR) region using previously obtained receiver function results as constraints for the inverted density profiles. We produce constrained crustal models that characterize the SRGR that show a shallower Moho (30 km) in the region, which is thicker than previously suggested. Based on the validation and implementation, we conclude that the algorithm using Primal-Dual Interior-Point methods is robust and always honors the geophysical constraints. Advantages of using this approach for structural inversion of gravity data are the incorporation of a priori information related to the model parameters (coming from actual physical properties of the subsurface) and the reduction of the solution space contingent on these boundary conditions.

*J08-P-05
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Gravitational signal produced by global shallow-Earth density model Litho1.0

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The global Earth's density distribution models based on data from seismic tomography and crustal compilations still improve in accuracy, lateral as well as in the vertical resolution. In our work, we evaluate the gravitational signal generated by such a model, Litho1.0, while focusing on the spectral properties. Litho1.0 provides about 10% of the total Earth's gravitational acceleration and allows to shed light on the spectral relations between the main "players" – the crust, the lithosphere and the upper mantle (as represented by the model). We also compare the results in terms of gravitational gradients with those obtained from the ESA's mission GOCE. The gravitational gradients depend less on deeper and more distant density variations than the gravity and therefore they provide suitable means for studying the shallow Earth. Finally, we discuss some numerical issues associated with the spherical tessellation used in Litho1.0 and LLNL-G3D.

*J08-P-06
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Deep Conductive Structure beneath the Kutcharo Caldera, Revealed by 3-D Inversion Analysis

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Kutcharo caldera is the biggest caldera in Japan, which has potential to cause catastrophic eruption. We think it is very important to clarify the current subsurface state of the volcano. There are some report for the caldera structure by gravity surveys and AMT explorations (e.g. Yokoyama, 1958, J. Phys. Earth; Honda et al., 2011a, J. Fac. Sci. Hokkaido Univ.; Ichihara et al., 2009, EPS), however, no obvious structures which associate any volcanic activities has been reported. We report the result of the 3-D analysis of the resistivity structure in and around the Kutcharo caldera.
Our survey was executed by wide-band and the long-period observations during 2009 and 2010. With our survey data, we compiled the wide-band MT data from Ichihara et al. (2009, EPS) and Ichihara et al. (2013, Tectonophys.), which are the observation data around the focal area of Teshikaga Earthquake. We adopted the remote reference analyses (Gamble et al., 1978, Geophysics) to these MT data. We used the reference magnetic data of Kakioka Magnetic Observatory and the Esashi station for the long wavelength and the wide-band data, respectively.
The three dimensional analysis is executed by WSINV3DMT (Siripunvaraporn et al., 2005, PEPI; Siripunvaraporn et al., 2009, PEPI). The characteristic resistivity structures found in the result is almost consistent with the result of the 2-D analyses (Honda et al., 2011). The extraordinary low resistivity body piercing the high resistivity layer towards the Atosanupri volcano from the deep layer was remarkable in the 2-D result. By the 3-D analysis, the conductor under the Kutcharo caldera became sharp.

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*J08-P-07
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Crustal structure beneath the eastern foot of the Japan Trench outer rise by airgun-ocean bottom seismometer survey

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Several studies on the seismic structure of the oceanic crust reported presence of evident reflectors in the oceanic lower crust or in the uppermost mantle although the seismic structure of the deeper part of the oceanic crust is thought to be relatively homogeneous. The presence of such reflective structure would be related to the processes of formation and/or growth of the oceanic crust. In this study, we investigate the crustal structure of the old Pacific Plate in the NW Pacific before it suffers from bending deformation at the trench to discuss the development process of the Pacific Plate by analyzing an ocean bottom seismometer (OBS) survey conducted in the eastern foot of the Japan Trench outer rise.

A traveltime analysis using a 2-D ray tracing method was made to construct a 2-D P-wave velocity model along the survey line. By assuming a low velocity zone (LVZ) in the lower oceanic layer 3, the observed appearance of the OBS records can be well explained. On the other hand, we applied a series of waveform analysis, combining a Seismic Interferometry (SI) technique and a NMO stacking, to obtain a reflection seismic profile by the OBS data, and then continuous and evident signal are imaged at ~9.0 s in two-way travel time (TWT). The TWT of the event is not consistent with that of the reflections from Moho discontinuity but is similar to that of the reflections from the top of the LVZ, if such reflection signals are actually observed.

We tried to apply the series of SI-NMO analysis to synthetic OBS seismograms calculated based on the velocity model with the LVZ in the layer 3. On the reflection profiles by the synthetic data, clear reflector events are identified at TWTs of ~9.0 s and ~9.7 s. The shallower reflector coincides with the top of LVZ. This test reinforces our interpretation that the reflections from the LVZ were imaged on the profiles derived by the field OBS data.

Velocity structure and Earthquake Distribution in Nagaoka Region

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The Nagaoka region is located on the high strain rate zone at eastern margin of Japan Sea, and it is also the area where the Chuetsu Earthquake and the Chuetsu-oki Earthquake have occurred. Between the two large faults, another faults are confirmed on the western margin of the fault zone of the Nagaoka plain. To investigate the activity of faults, the Association for the Development of Earthquake Prediction (ADEP) determined to newly construct a high-density seismic observation network (AN-net) in the region from 2010. In this study, we introduce the network and estimate the distribution of the earthquakes, and velocity structures in this region. AN-net consists of the 40 stations in the Nagaoka plane from November 2010. The size of the network is roughly 20km wide and 40 km long, covering the Nagaoka plain. In each station, the velocity seismometer and accelerometer at the bottom of a borehole which depth is about 100m, and another accelerometer is set on the ground. Half of the stations has GNSS stations. These data from each observation station are sent in real time. In this study, we calculate P- and S- velocity structure by Double Difference tomography. This method is used both absolute and relative arrival times. After 2010 when the AN-net was constructed, arrival times of each earthquakes is picked manually in the AN-net region. Before 2010 and region of the Surrounding AN-net, we get the arrival data from JMA unified earthquake catalog. The number of absolute P- and S-wave arrival times used in the tomography is 241,626 and 216,802, respectively, with the relative arrival times for the manually picked P- and S- waves reaching 993,390 and 858,086, respectively, from 13,353 earthquakes which occurred from October 1997 to 2016. The weighted root mean square (RMS) travel time residual was reduced 0.53s to 0.08s after 45 iterations. Based on the velocity structure, most of the earthquakes occurred at the depths where P-wave velocity is greater than 5.5km/s.

*J08-P-09
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Plate boundary property of the Philippine Sea plate revealed from later phase analysis beneath southwestern Ibaraki and northwestern Chiba prefectures, central Japan

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To investigate details of a possible disastrous earthquake beneath the Tokyo urban area, central Japan, knowledge about the plate boundary property is important. For this purposes, we studied later phases of natural earthquakes beneath the southwestern Ibaraki and the northwestern Chiba prefectures.
We found clear phases in vertical component of 1-4 Hz coherently in the MeSO-net (Metropolitan Seismic Observation network) line, between direct P and S arrivals (hereinafter, X phase). Traveltime difference between the X phase and direct P decreases for shallower earthquake. These features indicate that the X phase is converted from S to P above the hypocenter.
We compared observed traveltime difference and amplitude ratio between SP and direct P with synthetic values to cancel out surface structure effects, which were calculated using velocity structure and the upper boundary of the Philippine Sea plate (UPHS) determined by MeSO-net (Nakagawa et al., 2010; Hirata, 2012) with sedimentary layer (J-SHIS; Fujiwara et al., 2012). For amplitude calculation, radiation pattern expected from focal mechanism of NIED F-net or Hi-net, geometrical spreading, anelastic attenuation, and conversion or transmission coefficients on the UPHS were considered. Q of P and S waves were assumed to be 1000. Observed traveltimes were well explained. This indicates that the X phase is generated at the UPHS. On the other hand, small change in velocity structure was necessary to explain observed amplitude ratio. Estimated velocity exhibits large fluctuation, however, Vs was estimated to be 3 % slower on average just below the UPHS.
Since the target region is within the network of MeSO-net, reliability of the velocity structure and the UPHS are likely to be high. On the other hand, grid spacing is 5-10 km or larger, and hence structure smaller than this scale could not be imaged. Examination of amplitude ratio of later phase indicates small scale inhomogeneous structure around the UPHS.

*J08-P-10
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Heterogeneous structure in the incoming Philippine Sea plate along the Nankai Trough

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Rupture of large-thrust earthquakes along the Nankai Trough is known by always initiating from off the Kii Peninsula. The segmentation boundary between the 1944 Tonankai (Mw=8.1) and the 1946 Nankai (Mw=8.4) earthquake rupture is locate off the Kii Peninsula. Activity of the nonvolcanic deep low-frequency tremors and very low-frequency earthquakes observed around the down-dip limit of the coseismic rupture zone of the last Tonankai and Nankai earthquakes is not homogeneous, and the belt-like tremor zone is divided into several segments bounded by gaps [Obara, 2010]. Largest gap is recognized around the Kii channel between the Shikoku Island and Kii Peninsula.
Our recent integrated result of first-arrival tomography based on the 2012 and 2014 wide-angle OBS data shows dramatic along-trough variation in P-wave velocity just beneath the basement of the incoming Philippine Sea plate. Velocity change can be recognized south off the Cape Muroto and the Shima Peninsula just seaward of the trough axis. Such dramatic velocity change corresponds with the structural change in the configuration of the basement reflection in the time-migrated section. Similar along-trough structural variation can be recognized in the central Shikoku Basin far south from the trough axis [Nishizawa et al., 2011]. Heterogeneous structure along the trough may be related to the formation of the incoming Philippine Sea plate, because the structural boundary may correspond with the plate age of about 20-21.5Ma proposed by Okino [2015] based on magnetic lineation. This structural characteristic is thought to continue northwards to the subducting Philippine Sea plate beneath the southwest Japan, and may cause the segmentation of an earthquake rupture, and heterogeneous activity of low-frequency earthquake phenomena.
This study is part of ‘Research project for compound disaster mitigation on the great, earthquakes and tsunamis around the Nankai Trough region' funded by MEXT, Japan.

*J08-P-11

Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Detailed crustal and upper mantle structure of the subducting Philippine Sea plate and the overlying southwestern Japan arc, revealed by dense seismic array observation

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The Nankai trough region, where the Philippine Sea Plate (PHS) subducts beneath the SW Japan arc, is a well-known seismogenic zone of interplate earthquakes. A narrow zone of nonvolcanic tremor has been found in the SW Japan fore-arc [Obara, 2002]. Obara [2002] suggested fluids as a source for tremor. The behavior of fluids at the plate interface is a key factor in understanding fault slip processes. Seismic velocity variations can provide important information on the fluid-related heterogeneous structure. To reveal the subduction structure, we conducted passive seismic experiment in the eastern Kii Peninsula. 90 offline recorders were installed on a 90-km-long line during a six-month period from May, 2015. Arrival times of 275 local earthquakes were used in a joint inversion for earthquake locations and 3D Velocity structure. In order to investigate the relation of the crustal heterogeneity to the seismicity, we relocated 4,720 events occurring between January 1, 2000 and May 26, 2015, including 284 low-frequency earthquakes (LFEs), using the P- and S-wave arrival time data picked manually by the Japan Meteorological Agency and inverted 3D velocity model. We also applied a seismic interferometry technique to the local earthquake data set to obtain the geometry of the subducting PHS. Common-midpoint stacked profile of interferometric seismic imaging shows the northward-dipping reflector at a depth of about 25 km, which is interpreted as the top of the PHS. Most LFEs are located beneath the northward-dipping reflector. LFEs are located in and around the low Vp and high Vp/Vs zone. The low Vp and high Vp/Vs generally suggests the existence of fluid [e.g., Zhao et al., 1996], and indicates the occurrence of the LFEs may be associated with fluids. The epicentral distribution of LFE corresponds to the locked-sliding transition estimated by Hyndman et al. (1995). These studies suggest that fluids dehydrated from the PHS control frictional properties of the plate boundary.

*J08-P-12
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

3D seismic velocity structure beneath Kii Peninsula, southwestern Japan derived from receiver function analysis and seismic tomography

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1. Introduction
In order to investigate behavior of slab-derived fluids discharged from the Philippine Sea plate subducting beneath Kii Peninsula, southwestern Japan, we carried out seismic observations, receiver function analysis and seismic tomography. We estimated the geometry of the slab and the seismic velocity structure beneath the Kii Peninsula, and discussed the behavior of the fluids with the distribution of low velocity anomalies.

2. Receiver function (RF) analysis
We carried out linear array seismic observations in the Kii Peninsula from 2004 to 2013. We deployed seismometers along six profile lines with an average spacing of about 5 km. We applied RF analysis and obtained images of S wave velocity discontinuities. We estimated 3D configurations of the continental Moho, the slab top and the oceanic Moho from RF images for the six profile lines.

The continental Moho, the slab top and the oceanic Moho are clearly found in the RF images. A new knowledge obtained by the analysis is that the continental Moho dips upward in the southeast direction above the Philippine Sea slab.

3. Seismic tomography
We carried out the tomography with FMTOMO (Rawlinson et al., 2006). We used a velocity model with the 3D geometries of the three discontinuities derived from the RF analysis. We used 231,650 P travel times and 210,142 S travel times observed at the temporary stations in addition to permanent stations.

Results of the tomography show that low velocity anomalies (> 5 % in both P and S wave velocities and high Vp/Vs ratio > 1.8) are located in deep low frequency events areas at 30 – 40 km depths on the Philippine Sea slab and that another strong low velocity anomaly (> 10 % in P wave velocity and low Vp/Vs ratio < 1.6) is widely distributed in the lower crust beneath the northern Wakayama Prefecture where small to micro earthquake activity is very high in the upper crust.

We used waveform data from stations of NIED; JMA; ERI, Univ of Tokyo; Nagoya Univ and DPRI, Kyoto Univ.

*J08-P-13
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Crustal velocity structure and configuration of the subducting Philippine Sea plate beneath the Japanese Islands identified from receiver function analysis

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We apply receiver function analyses to estimate the velocity structure in the crust and uppermost mantle and configuration of the subducting Philippine Sea plate beneath the Japanese Islands. The velocity structures beneath each seismic station searched a best-correlated model between an observed receiver function and synthetic one by using a grid search method. We further constructed many vertical cross-sections of the estimated velocity structure models and the depth-converted receiver function images to estimate seismic velocity discontinuities. Repeating earthquake data which occurred in the subducting plate boundary were also used to estimate plate geometries.
The configuration of Philippine Sea plate dips toward the northwest beneath the Japanese Islands. The direction coincides with plate motion. The thickness of the Philippine Sea plate gradually decreases to the northeast after the contact with the underlying Pacific plate beneath the Tokyo metropolitan area. The northeastern margin of the Philippine Sea plate can identify from the decreasing plate thickness. In the subducting plate boundary contacted with the island arc Moho, we identify non-volcanic tremors in the southwestern Japan region and normal earthquakes including small repeating earthquakes in the Ryukyu Islands. The former areas are characterized by high-velocity mantle wedge and low-velocity oceanic crust, whereas relatively low-velocity mantle wedge characterizes the latter areas. Source regions of past inter-plate destructive earthquakes seem to correspond to the high-velocity area in the Philippine Sea slab. These observations may indicate the relationship between slip characteristic of the plate interface and serpentinized materials which reflect dehydration of the subducting oceanic crust.

*J08-P-14
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Geometry of the frontal thrust at the trench axis around the Hyuga-nada region revealed by high-resolution seismic reflection imaging

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Great earthquakes with tsunamis with recurrence intervals of 100–200 years have occurred along the Nankai Trough near central Japan. Hyuga-nada is located in the western part of Nankai Trough, subducting the Kyushu-Palau ridge which is remnant arc constructed by backarc spreading in Shikoku Basin. New tsunami source model of historical tsunamigenic earthquake (e.g. 1707 Hoei) is extended to Hyuga-nada region revised by inundated deposits at coastal lake in Kyushu. Recent ocean-bottom monitoring results have also yielded presence the episodic low-frequency tremor associated with the activity of very-low-frequency earthquake at shallow plate interface at the northern end of subducting Kyushu-Palau ridge.
In order to understand the geometry of the frontal thrust around the Kyushu-Palau ridge, a dense high-resolution seismic reflection survey was conducted by Japan Agency for Marine-Earth Science and Technology over 600 km of line length from Sep. to Oct., 2016 using R/V Yokosuka.
Clear seismic reflection images of frontal thrust in the accretionary prism, trench-fill deposits are shown around the Kyushu-Palau ridge from preliminary profiles. The distribution of trench-fill sediments is limited to only the east side of Kyushu-Palau ridge. There is no deformation structure in the trench-fill sediments from the trench axis to the seaward region. In the west side of Kyushu-Palau ridge, there are few sediments on the subducting oceanic crust. These characteristics suggests that the crustal structure at the trench axis around the Kyushu-Palau ridge is not “typical" Nankai subduction zone. Although our surveys covered a part of Nankai seismogenic zone, it is important to understand the deformation process of the western part of Nankai Trough.
This study is part of "Research project for compound disaster mitigation on the great earthquakes and tsunamis around the Nankai Trough region" funded by the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

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Three-dimensional P- and S-wave attenuation tomography in the Ryukyu Arc, Japan

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We investigate 3D seismic Qp and Qs structures in the Ryukyu Arc. It is important to estimate the 3D Q structure in this region, since there are highly active volcanoes and seismicity between the Okinawa Trough and the Ryukyu Trench. We use seismic waveform data recorded by seismic observation networks of NIED, JMA and Kagoshima University, from 2004/06 to 2014/05. We select 4,353 seismic events, which the range of JMA magnitude is greater than or equal to 3.0 and less than or equal to 6.0. The corner frequency of the source spectrum for each event is estimated by using scaling law before calculating the attenuation quantity t^*. The t^* is estimated from the amplitude decay rate from the source-corrected spectra between 3.0-30.0 Hz. 21,089 P- and 17,939 S-wave t^* are obtained. We then invert the P- and S-wave t^* data to 3D Qp and Qs distributions by a tomographic technique using the non-negative least squares method. For the inversion, the coordinate center is located at (127.0E, 26.5N). The coordinate system is rotated counterclockwise 42 degrees from north. We confirm that this axis rotation can improve the result of the checkerboard resolution tests (CRTs). Our estimated Qp and Qs structures has remarkable features: low-Qp and Qs zones exist beneath the Okinawa Trough, where is an extensional field along the rift. Low-Qp and Qs patches are located beneath active volcanoes in the Tokara islands. These patches may indicate upwelling of high temperature materials from top of the high-Qp and Qs Philippine Sea (PHS) slab. Low-Qp and Qs spots are also located in the forearc side. Especially, these spots in Kikai Island and Hateruma Island may denote sediment or accretionary prism.

*J08-P-16
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Inhomogeneous rifting structure in the northern Okinawa Trough, an active backarc basin southwest of the Japan Islands

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The Ryukyu (Nansei-Shoto) island arc–trench system is located at a convergent plate margin where the Philippine Sea (PHS) plate is subducting under the Eurasian plate. The Okinawa Trough is a backarc basin of the system extending from north to south and the stage of its ongoing rifting process varies along the trough. The crustal extension in the northern trough is not progressing so much compared with the southern trough. The position of the trough axis is not determined clearly in the northern trough, though it corresponds to several en echelon narrow rifts in the southern trough. The seafloor topography in the northern trough shows different features between the eastern and the western parts. Because the volcanic front related to the PHS plate subduction exists in the eastern part, there are many seamounts and knolls in this part. In contrast the western part is rather flat seafloor.
We have conducted multi-channel seismic (MCS) reflection surveys to acquire detailed images of deformation in shallow structures reflecting variable tectonic backgrounds of the Okinawa Trough since 2008. We fired a trigun cluster with a total volume of 1,050 cubic inches at a 50 m shot interval and used 240-channel (3,000 m long) seismic streamer. The MCS data were processed by a standard procedure including band-pass filter, deconvolution, normal move out correction and CMP stacking.
The MCS results reveal a number of normal faults and intrusions beneath all the seismic lines inside the northern trough. In the western part of the trough with a flat seafloor, there are thick sedimentary layers with over 3,000 m thick at most. However we detected several intrusions below the seafloor and some of them penetrate into the uppermost sediments. On the contrary, the eastern part shows the rough seafloor and the existence of many volcanic features. The MCS profiles reveal many igneous intrusions reaching above the seafloor, which corresponds to the volcanic front in this region.

*J08-P-17
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

Mantle heterogeneity in the oceanic lithosphere of the southwest sub-basin, South China Sea, from the wide-angle seismic and the gravimetric model

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The southwest sub-basin (SWSB) of the South China Sea (SCS), an oceanic basin, locates in the southwestern part of the SCS, separated by several rigid blocks, influenced by a direction changing spreading center and ridge propagation until the asthenosphere stopped upwelling around 15Ma. The processes of seafloor spreading through a series of mantle lithospheric dynamics in the oceanic lithosphere is generally considered to be the consequence of melt extracting and crustal accretion in the upper mantle structure. Lateral crustal heterogeneity only plays a minor role in geophysical attributes, since the crustal structure can be revealed by the modeling of wide-angle seismic traveltime and amplitude. After the calculation of the residual mantle gravity anomaly (RMA), we can do inversion about the upper mantle density variations across the axis in 3-D. Taking account of the crustal structure, cold thermal structure with a strong lithosphere means anisotropic magma distribution along the slow-spreading ridge, which leads a heterogeneity mantle's density structure across the ridge. Therefore, the upper mantle structure, inferred from wide-angle seismic and gravity can thus provide us with knowledge of the processes that have formed oceanic lithosphere at different times and under a variety of conditions which is a straightforward response of the deep mantle structure of the lithosphere. By inverting the RMA of the SWSB in the SCS, its distinct low anomaly over the fossil spreading centre, little variation along the direction of the paleo-spreading axis direction, and relatively wider area of high anomaly on the southeast side, the density variation indicates the changing of the direction may leave space for melt accretion in the northern flank of the spreading ridge, and squeeze the limited off-axis space in the southern side, which may be the reason that more melt was retained on southern flank of fossil ridge.

*J08-P-19
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

The 3-D velocity structure of the 2008 Taoyuan Earthquake Sequence in Kaohsiung, Taiwan

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The three-dimensional velocity structure of the upper crust was determined by using the arrival readings were identified from the 2008 Taoyuan Earthquake Sequence. On March 4, 2008, a moderate earthquake (ML 5.2) occurred in Taoyuan district of Kaohsiung City in southern Taiwan. It was followed by numerous aftershocks in the next 48 hours, including three events with magnitude larger than 4. The high-resolution waveform data of this sequence were well-recorded by a large number of recording stations. These stations belong to several different permanent networks (operated by IES, NCU, and NCCU) and temporary networks (deployed by TAIGER project, Taiwan Integrated Geodynamic Research project) all around Taiwan. All waveform data are managed and processed by Antelope software suite. We applied a 1-D velocity model for locating events in the preliminary analysis. In this study, we introduced the double-difference tomography method not only to determine the fault geometry of the main shock but also to investigate the detailed 3-D velocity structure in this area. The results indicate that aftershocks are extended along the NE-SW direction and located on a 45 SE-dipping plane, which agrees with one of the nodal planes of Global CMT solution (strike = 45, dip = 40, and rake = 119). We can identify a clear low-velocity area which is enclosed by events next to the main shock in the final 3D velocity model. We also recognized a 45 degree-dipping zone, which is extended to the ground surface with low-velocity; meanwhile, velocity structure variation in study area corresponds to major geologic units in Taiwan.

*J08-P-19
Joint Symposium / J08. Imaging and interpreting lithospheric structures using seismic and geodetic approaches

The shallow structure of Tatun Volcano Group from residual gravity and magnetic data

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Tatun Volcano Group (TVG) is composed by 21 volcanoes, located in northern Taiwan. It is a very important topic to understand the background of volcano group, especially which is nearby Taipei city, the largest city in Taiwan. In this study, the new magnetic surveys (372 points) and gravity data combinations (246 points) of TVG are processing. After data processing and correction, new gravity and magnetic anomaly maps are showed. The anomaly maps are fitting well with volcanic and igneous rocks. For modeling TVG structures near shallow surface, the filters are used to show the regional and residual map from the gravity and magnetic maps. The gravity inversion and magnetic analyses are also used in the next step. Final, in the gravity results, TVG is covered by high density andesitic lavas, especially around two major peaks (Tatun and Chihsing Mts.). The Curie Point Depth in TVG from magnetic data also provide the high thermal gradient area beneath Tatun and Chihsing Mts.

*J09-1-01
Joint Symposium / J09. Geodesy and seismology general contributions

Normal-faulting earthquakes in the northern area of Ibaraki Prefecture, Japan in 2011 and 2016 - Duplicate events detected by InSAR observations -

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Following the 2011 Tohoku earthquake, many inland crustal earthquakes have occurred with a source mechanism of normal fault motion in the Fukushima hamadori and northern Ibaraki areas, Japan. Under such a seismological background, an inland earthquake with a moment magnitude (Mw) of 5.9 occurred in the northern area of Ibaraki Prefecture at 21:38 on Dec. 28, 2016. The startling finding derived InSAR observations is that location, spatial distribution, and magnitude of the InSAR-derived crustal deformation is almost same as those observed for the inland earthquake that occurred with Mw6.1 on March 19, 2011. The InSAR result shows that the deformation has ear-shaped distribution, elongated along the north-south orientation. Another remarkable feature is that a displacement discontinuity with a length of about 2 km is clearly recognized in the northeast of the source region, probably suggesting that a rather shallow slip occurred. The same features were identified in the 2011 event, and in particular, it is surprising that both the position and the length of the discontinuities are the same between the two events.
The fault model for the 2016 event that consists of two fault segments shows (1) west-dipping fault planes with dip angles of 50–60 deg, (2) NNW-SSE (NW-SE) strike direction, (3) nearly pure normal fault motions, and (4) a shallow local slip. The 2011 event also has almost the same features on the fault model (Kobayashi et al, 2011). It strongly suggests that almost the same fault slips have occurred on almost the same fault plane for both the events, which is probably the world's first observation in that we can identify the similarity "visibly".

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Recent findings on dual tsunami sources: November 1945 Makran (NW Indian Ocean) and December 1908 Messina (Italy) tsunamis

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The concept of dual (combined earthquake-landslide) tsunami source has gain weights in tsunami community mostly since the July 1998 Papua New Guinea tsunami where only a dual source was capable of re-producing the coastal runups [Satake & Tanioka, 2003, PAGEOPH; Tappin et al. 2001, Mar. Geol.]. Since then, efforts have been made to re-analyze historical tsunami events in order to address discrepancies between available observations and numerical results based on the state-of-the-art models. Such efforts have helped to find potential locations of co-seismic submarine landslides [e.g., Billi et al., 2008, GRL]. Improved understanding on the mechanism and case studies of dual tsunami sources are vital in accurately mapping the coastal hazards. Here, we discuss two case studies of dual tsunami sources: 1945 Makran (NW Indian Ocean) and1908 Messina (Italy) tsunamis. In a recent study, Heidarzadeh and Satake (2017) [BSSA] showed that the extreme runup of 12-15 m reported in the near-field for the 1945 Makran tsunami was possibly due to a dual source: a 220-km earthquake fault with average slip of ~6 m and a submarine landslide with dimensions of 15 km (length) x 15 km (width) and a thickness of 600 m. Landslide volume was estimated at ~40 km3. The other heavily debated tsunami event is that of December 1908 in Messina whose origin is still debated. Although several earthquake faults have been proposed for this event, none of them has reproduced the observations [e.g. Tinti and Armigliato, 2003, Mar. Geol.]. Landslide sources were proposed for this event based on the limited marine geophysical data with varying success [e.g. Billi et al., 2008, GRL; Favalli et al., 2009, GRL]. New marine geophysical data obtained for the region [Lili et al., 2017, GRL, in revision] helped to more accurately map potential submarine landslide and more accurately model potential tsunamis in this region. We propose a new dual tsunami source for the 1908 Messina tsunami.

*J09-1-04
Joint Symposium / J09. Geodesy and seismology general contributions

Tsunami source of the 1979 Tumaco Earthquake estimated from historical tide gauge records and geodetic data

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On December 12, 1979 an earthquake occurred in southern coast of Colombia , in front of Tumaco area (1.60N 79.36W, 07:59:03.300 UTC according to U.S. Geological Service). The surface-wave magnitude of this event was estimated as Ms7.7 (USGS), and its moment magnitude was calculated as Mw8.1 (GCMT Catalog). The epicenter was located 80 km southwest of Tumaco, offshore the Pacific coast of Colombia. This event generated a tsunami that killed more than 100 residents of San Juan Island, 60 km north of Tumaco. The observed coastal subsidence, due to the coseismic deformation, was approximately 0.50 m near Tumaco area (Herd et al., 1981).
This study aims to investigate the tsunami source of the 1979 Great Tumaco Earthquake using inversion of historical recorded tsunami waveform and geodetic data. We employ the tsunami signal recorded at three tide gauge stations (Esmeraldas and Santa Cruz in Ecuador, and Acujutla in El Salvador). To estimate the extent of the tsunami source and the slip distribution, we divide the tsunami source into 5 x 2 subfaults along the strike and dip directions, respectively. The assumed fault area covers the aftershock distribution during one month after the mainshock. The subfault size is 40 km x 40 km with top depths of 12.9 km and 24.0 km. The focal mechanisms for all the subfaults were taken form the GCMT solution of the mainshock. The inversion result using only tsunami data, and the joint inversion of tsunami and geodetic data showed that the largest slip was located north the epicenter with an average slip of 5.4 m. The estimated moment magnitude from both inversion models was nearly identical Mw=8.03 (1.38E+21 N-m), which is slightly smaller than the published by GCMT (Mw=8.1, moment 1.60E+21 N-m). The estimated slip distribution suggested that the fault rupture started near the epicenter and propagated northeast, which is also supported by the aftershock distribution (Herd at al., 1981).

Crustal blocks motion model and interplate coupling in Colombia based on GNSS observation network (GEORED)

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Introduction
Colombia is located at the boundary between South-America plate, Nazca Plate and Caribrian plate. This region is very complexes such as subducting Caribrian plate and Nazca plate, and collision between Panama and northern part of the Andes mountains. The previous large earthquakes occurred along the subducting boundary of Nazca plate, such as 1906 (M8.8) and 1979 (M8.2). And also, earthquakes occurred inland, too. So, it is important to evaluate earthquake potentials for preparing huge damage due to large earthquake in near future.

GNSS observation
In the last decade, the GNSS observation was developed in Columbia. The GNSS observation is called by GEORED, which is operated by servicing Geologico Colomiano. The purpose of GEORED is research of crustal deformation. The number of GNSS site of GEORED is consist of 93 continuous GNSS observation site at 2016. The sampling interval of almost GNSS site is 30 seconds. These GNSS data were processed by PPP processing using GIPSY-OASYS II software. GEORED can obtain the detailed crustal deformation map in whole Colombia.

Method
We developed a crustal block movements model based on crustal deformation derived from GNSS observation. Our model considers to the block motion with pole location and angular velocity and the interplate coupling between each block boundaries, including subduction between the South-American plate and the Nazca plate. And also, our approach of estimation of crustal block motion and coefficient of interplate coupling are based on MCMC method. The estimated each parameter is obtained probably density function (PDF).

Result
We tested 11 crustal block models based on geological data, such as active fault trace at surface. The optimal number of crustal blocks is 11 for based on geological and geodetic data using AIC. In this presentation, we will discuss spatial interplate coupling ratio and also earthquake potential at inland faults.

Rise Time of Coseismic Tectonic Deformation during Megathrust Earthquakes , as estimated from Observed Low-Frequency Acoustic-Gravity Waves

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Unusual low-frequency acoustic-gravity waves with periods up to as long as 14 min have been recorded after four megathrust events. These are the 1964 Alaskan earthquake (Mw=9.2), the 2004 Sumatra-Andaman earthquake (Mw=9.2), the 2011 Off-Tohoku earthquake (Mw=9.0), and the 2010 Maule, Chile (Mw=8.8) earthquake, respectively. These extremely long-period atmospheric waves have been clearly observed at several microbarograph stations located at not only several regional stations but at many International Monitoring System stations even up to a far-field of 6,700 km. The phase and group velocities of these disturbances are found to be between 314 m/s to 364 m/s consistent with so far predicted for acoustic-gravity waves.

These observed low-frequency atmospheric waves may be interpreted as excited by upheaval and depression of the sea surface within the extensive source region of these extremely large thrust earthquakes due to coseismic uplift and subsidence of the sea bottom. We calculate the synthetic waveforms for the propagating atmospheric disturbances due to the coseismic vertical displacements of the sea surface, incorporating a standard sound velocity and density structures up to an altitude of 220 km above the earth's surface. The calculated waveforms for many stations well explain most of the observations. Our analysis suggests the initial coseismic change of the sea surface in the main part of the source region may exceed 4 – 6 meters with the rise time between 2 and 4 min depending on their locations, which is related to the source process of these megathrust earthquakes.

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Joint Symposium / J09. Geodesy and seismology general contributions

Resolution analysis for earthquake kinematics inversion

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Until recently, little attention has been devoted to the assessment of the quality of the solution in most geophysical inverse problems. The clear difference between optimal solutions, obtained by different proposed algorithms, has driven researchers interest to not just get a solution but to state its confidence in it. For earthquake kinematics inversion, the uncertainty quantification has been very little explored. However the research community has clearly pointed out that it is a main research topic because of the different solutions obtained in some specific benchmarks (Mai et al. (2016)).

The purpose of an earthquake kinematics inversion is to get the slip-rate time-space history using the seismograms available. A simple way to evaluate its resolution length is to perform a checkerboard test. However multiple tests must be done in order to identify the specific resolution length in different regions of the solution. Fitchner and Van Leeuwn (2015) have proposed to use random probing techniques for resolution analysis. They have pointed out that the Hessian acts as a smoother of random functions which carry information of the resolution.

In this work we show how to perform a resolution analysis for earthquake kinematics inversion based on stochastic probing of the Hessian operator. The strategy is to compute the Hessian vector product of some random vectors, then perform the autocorrelations of the product vectors and finally average all the autocorrelations to get the time and spatial resolution lengths. The Hessian vector product is done through a second-order adjoint strategy that allows to avoid the explicit Hessian computation.

*J09-2-02
Joint Symposium / J09. Geodesy and seismology general contributions

Effect of frictional properties of minerals in the crust on the depth of seismic faulting

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Depth and width of seismogenic zones seem to result from the nature of the friction of materials which form the crust. Frictional properties of materials, which depend on the environmental conditions such as temperature and water content, control the depth which divided between the stable region where earthquakes don't occur and the unstable region where earthquakes take place. For example, laboratory experiments revealed that a small amount of quartz added to the composite materials has a stabilizing effect, resulting the unstable to stable behavior of the mixture materials. Here we measured frictional properties of quartz and feldspar, major minerals of the crustal rocks, under high pressure and high temperature conditions, in order to understand the effects of frictional properties of minerals in the crust on the depth range of seismogenic region. We found that there are temperature ranges correspond to the unstable regions for both quartz and feldspar under the wet condition and that the unstable temperature region of quartz is narrower than that of feldspar. These results suggest that the frictional properties of constituent materials in the crust critically affect the seismic faulting depth and the seismogenic processes.

*J09-2-03
Joint Symposium / J09. Geodesy and seismology general contributions

Flexural mechanics and curvature evolution of the bending-unbending transition zone of subducting oceanic lithosphere

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1. Introduction
Oceanic lithosphere is bended just before subduction, and is un-bended sooner or later after it subducts from the trench. Many previous studies analyzed flexure of the oceanic lithosphere in outer rise from topography and gravity anomalies for estimating the strength and rheology of the oceanic lithosphere [e.g., Goetze and Evans, 1979; Hunter and Watts, 2016]. The targets of their studies were limited to offshore from the trench, and flexural mechanics of subducting part of the oceanic lithosphere is poorly understood. Thus, the purpose of this study is to clarify the flexural mechanics of the bending-unbending transition zone of subducting oceanic lithosphere.

2. Method
This study expanded the flexural analysis to subducting part (up to 50 km depth) and estimated curvature evolution of the oceanic lithosphere in the bending-unbending transition zone. The target is the Pacific plate subducting from the Japan Trench (120-130 Ma).
First, we estimated the bending moment evolution of the Pacific plate from topography and gravity anomalies. Next, we conducted a numerical model of bending-unbending of the oceanic lithosphere in order to investigate how the bending moment develops with curvature. Finally, we estimated the curvature evolution of the bending-unbending transition zone of the Pacific slab by fitting modeled bending moment with estimated it from topography and gravity anomalies.

3. Results
When unbending initiates after bending, residual bending stress is released elastically. Thus, only slight curvature changing causes rapid bending moment changing. However, spatial changing of the bending moment must be gradual to satisfy force equilibrium. Consequently, curvature changing in the bending-unbending transition zone must be much slow. This result will be useful to constrain maximum curvature of subducting oceanic lithosphere for estimating e.g., bending energy dissipation.

*J09-2-04
Joint Symposium / J09. Geodesy and seismology general contributions

Vertical Deformation Following Groundwater Drawdown by Excavating of 500 m Depth Shafts in Granite in Mizunami, central Japan in 2004-2016

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Two investigation shafts of 500 m depth were excavating in the granite body in Mizunami, central Japan by JAEA (Japan Nuclear Cycle Development Institute) in 2004-2012. Groundwater of 800 ton is generally pumping a day to prevent the shafts from submerging now. As a result of pumping the groundwater, the ground water level lowered to 80 m in the borehole with the distance of 200 m from the excavating shafts in 2016.Leveling network extending 2 km x 2 km around the shafts was established to detect the vertical deformation around the shafts in 2004, and precise leveling was done every year. An 18 mm ground subsidence was detected in the benchmark close to the shafts for 8 years in 2004-2012, and time series of subsidence at benchmark was consistent with the groundwater drawdown. The groundwater drawdown and ground subsidence were caused by the pumping ground water in excavating shafts.
In 2012, we extended the leveling network to a width of 4 x 5 km around the excavating shafts, and we had precise leveling at the network every year since 2012 to 2016. As results, subsidence of 8 mm is detected in the area in the southeastern are from the shafts side.
A depth distribution of granite in the area is estimated from aeromagnetic surveying. As results, two groundwater veins are suggested in NW to SE and NNE to SSW. Beneath the shafts, groundwater is flowing to southeast from northwest. A subsidence of 8 mm is detected along the groundwater, not only vicinity of the shafts. It is a good fruitful result to make clear the ground deformation by precise leveling.

ISC-EHB: Reconstructing the EHB Earthquake Database

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The EHB database was originally developed with procedures described by Engdahl, Van der Hilst & Buland (1998), and it currently ends in 2008. It is a widely used seismological dataset, which we aim to expand and recreate, partly by exploiting the updated procedures at the International Seismological Centre (ISC), to produce the ISC-EHB. We begin with events in the modern period (2000-2014) and apply new and more rigorous procedures for event selection, data preparation, processing, and relocation.
The ISC-EHB criteria selects seismic events from the ISC Bulletin which have more than 15 teleseismic (> 28º) time defining stations, with a secondary teleseismic azimuth gap of < 180º, and a prime magnitude > 3.75 (Di Giacomo & Storchak, 2016). These criteria minimize the location bias produced by 3D Earth structure, and select many events that are relatively well located in any given region.
There are several processing steps; (1) EHB software relocates all the events using ISC starting depths; (2) Near station and secondary phase arrival residuals are reviewed and a depth is adopted or assigned according to best fit, and in some instances depths may be reassigned based on other sources (e.g., USGS broadband depths); (3) All events are relocated with their new depths and plotted in subduction zone cross sections, along with events from the ISC-GEM catalogue for comparison; (4) These plots are used to confirm or modify weakly constrained depths.
The new ISC-EHB database will be useful for global seismicity studies and high-frequency global tomographic inversions. This will be facilitated by online access to the ISC-EHB Catalogue and Bulletin via the ISC, and will include maps and cross sections of the seismicity in subduction zones. Example maps and cross sections for events in years 2000-2003 will be presented.

*J09-2-06
Joint Symposium / J09. Geodesy and seismology general contributions

The ISC Bulletin and the derivative datasets for Geoscience research

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The International Seismological Centre (ISC) produces the global definitive Bulletin of earthquakes and other seismic events based on reports from over 130 seismic networks worldwide. The ISC Bulletin remains the most long-term and comprehensive source of information for global seismicity between 1904 and 2017. In addition to earthquake hypocentres and magnitudes, the historical period (before 1964) now contains seismic arrival times at stations from the International Seismological Summaries (ISS) and multitude of individual station bulletins digitized during the ISC-GEM project. The modern period (1964-onwards) is currently being updated, expanded and homogenized under the Bulletin Rebuild project.

To help users with different research needs/requirements, we also maintain and distribute several derivative datasets:

The ISC-GEM catalogue – the most homogeneous and complete record of moderate to large instrumentally recorded earthquakes over the last ~110 years; it was designed for use in global and regional assessment of seismic hazard.

The ISC-EHB bulletin - a groomed subset of the ISC Bulletin containing well-recorded teleseismic events with particular attention given to depth determination; it is widely used in studies of seismicity and structure of the Earth.

The IASPEI Reference Event List (GT) – a bulletin of events for which the hypocentral information is known with high confidence (to 10km or better); it is used for a variety of calibration purposes, especially in nuclear monitoring studies.

The ISC Event Bibliography - an interactive facility that enables searches for references to scientific articles devoted to individual natural and anthropogenic seismic events that occurred within a region and time period of interest; it is widely used in education and by scientific article authors, reviewers and journal editors.

We describe major advances recently made by the ISC to extend and improve these open-access datasets that are widely used in Geoscience research.

*J09-3-01
Joint Symposium / J09. Geodesy and seismology general contributions

Temporal change in transfer function using ACROSS associated with magma intrusive event in 2015 in Sakurajima volcano, Japan

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We detected a temporal change in propagation property of seismic wave associated with a magma intrusive event on 15 August 2015 of Sakurajima volcano, Japan. The propagation property, which is called transfer function (Green's function), has been monitored continuously since 12 September 2012 using an accurately-controlled seismic source (ACROSS) and seismic stations in Sakurajima volcano island. The change in the transfer function was calculated with 2-hour resolution. Large change is detected in the initial stage of the intrusive event, when the rate of crustal deformation was maximum. The amount of change associated with the intrusive event shows a spatial variation, depending on the location of the seismic stations. We calculated cross covariance between the transfer functions before and after the event. The cross covariances for the stations in the direction of summit crater from the ACROSS source show larger reduction than those in the peripheral area even for the stations of comparable distance from the ACROSS source. The stations that show large reduction of cross covariance also show phase advance toward coda part, meaning velocity increase of the media. The amount of velocity increase is estimated to be about 1%. This indicates that the velocity increase is caused by the stress increase due to the magma intrusion. The stations in the peripheral area, which shows little reduction of cross covariance, also show little velocity change even in the same direction from the intrusion source. This may result from spatial variation of stress sensitivity of the medium in the volcanic body. The material in the central part of Sakurajima volcano is more sensitive to stress probably due to less compaction of eruption material.

*J09-3-02
Joint Symposium / J09. Geodesy and seismology general contributions

Secular and co-seismic velocity changes in Tokai region detected by ACROSS

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We detected secular and co-seismic travel time changes and their anisotropy using active seismic measurement in the Tokai region, Japan. In this study, we used seismic signals generated by ACROSS, which is a highly stabilized artificial seismic source, to measure propagation properties of seismic waves. The high stability of ACROSS signal makes us possible to detect very small changes of physical properties in the crust. The ACROSS signal is received by High sensitivity seismograph network Japan (Hi-net) stations to calculate a transfer function from the ACROSS source to each Hi-net station in the Tokai region during 2007 to 2014. The transfer functions show secular and annual change in the travel time of S-wave throughout the observation period. A large co-seismic change is also observed at the time of the 2011 Tohoku-Oki Earthquake. Considering S/N ratio, we focused on the stations near the ACROSS source. We found that the travel time was gradually advanced in the observation period and were suddenly delayed associated with earthquakes, which caused strong motion in this area such as Tohoku-Oki earthquake. Due to high S/N ratio at the nearest station, which is about 3 km from the ACROSS source, post-seismic travel time change shows a gradual recovery just after the sudden delay at the time of the Tohoku-Oki Earthquake with a time constant of one month. However travel time was not recovered to their original level. Next, we analyzed polarization anisotropy of the travel time changes. At the almost stations, the advance rate of the secular changes were the largest in NE-SW direction, and the co-seismic delay associated with the Tohoku-Oki earthquake were also the largest in NE-SW direction. The two anisotropies are very similar in direction, though the sense of travel time changes are opposite. We are trying to create a model that can explain these anisotropies by comparing with crustal strain change measured by GNSS and other geophysical observations.

*J09-3-03
Joint Symposium / J09. Geodesy and seismology general contributions

Tracking of water level of dam reservoir by using a broadband seismometer

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We found distinctive incessant monochromatic oscillations with a frequency around 10 mHz by analyzing STS-2 broadband seismometer data of the F-net IGK station at Ishigakijima, Okinawa, Japan. The possible origin of oscillation is seiche (water level oscillation) of dam reservoir in the vicinity of the seismic station. We show the frequency variations of the mode for five years (2012-2016) based on STS-2 seismograms. Observed frequency variations are in good agreement with water level change of dam reservoir compiled from dam observation daily reports. And we discuss implications for long-term monitoring hydrological condition and/or the state of the seismometer system.

*J09-3-04
Joint Symposium / J09. Geodesy and seismology general contributions

About 38mHz (26 s) oscillation in northeastern Japan after the 2011 Tohoku megathrust earthquake

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By stacking high-rate GNSS data at north-eastern Japan, we find a peaky signal with frequency of about 38 mHz (26 s) following the 2011 Tohoku earthquake in the horizontal-to-vertical (H/V) spectral ratio. The signal appeared several minutes after the passing of surface wave fronts, and its duration was about 2 min. Since the frequency of 38 mHz was almost equal to the world-wide microseism (Oliver, 1962; Shapiro et al., 2006), we speculate that some features of the Earth's structure contributed the characteristic oscillation.

*J09-3-05
Joint Symposium / J09. Geodesy and seismology general contributions

Different Application of Ultrasonic Underwater Particle-Tracing Probes at Deep Ocean Floor

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Vertical or horizontal dislocations of the oceanic crust can provide some slow current changes at deep seafloor as an auxiliary pre-indicator of tsunami or earthquake.
The use of different forms of piezoelectric probes is an advanced method when performing particle motion and dimension analysis. Array based probes, for example, can measure density and velocity with directional item for suspended or drifting materials on the seabed. Their working capabilities are rather high, due to crystals' efficient trigger force at high pressure. Advantage of P-wave is observing ability to "sequentially hidden (or masked) particles" moving at the background. This is impossible for other methods based on such as light diffraction, conductivity or magnetic field sensing, under the presence of mass shadow effect. In fact, linear, differentiated linear, circular, spherical, concave shaped array forms are all possible in practice. The future design of spherical and "digitally driven and displaceable point source probes" may take time. The computer-controlled surface area of a displaceable point source can be devised for any given desired field scale. Suitable software can create artificially 'relatively portable and formed source field areas' from the transducer surface. Using three linear probes which would be along the main dimensional axes (magnetic north considered x,y,z) will consume three times higher energy than a single probe with separated sections on three axes; as it needs three interpreter circuits.
The scanning velocities of the probes have variability depending on the gaps between their piezoelectric crystals. In addition, sensor station's 'positioner flaps' cannot be efficient at low-velocity deep-currents because bio-foliation and corrosion decreases life time for accurate measuring of device by some friction problems on mechanical devices (positioner rudders). Spherical probes will particularly be the best particle observers with their non mechanised settings.

*J09-4-01
Joint Symposium / J09. Geodesy and seismology general contributions

CURRENT IMPORTANCE OF THE CHILEAN NATIONAL GEODESIC NETWORK IN A COUNTRY SUBJECT TO EARTHQUAKES.

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The Military Geographic Institute of Chile (IGM) is the Official Organization responsible for maintaining the National Geodesic Network (RGN) and participates in the Geocentric Reference System for the Americas (SIRGAS). At the IGM, the “SIRGAS-Chile Data Processing and Analysis Centre" manages the geodesic networks that constitute the horizontal and vertical reference systems and the permanent GNSS stations.

The IGM, together with the National Seismological Centre (CSN), has integrated the RGN with the National Seismological Network (RSN), setting up a single geodesic network, processed and analyzed by the IGM to serve in supporting the geo-referencing of geoscience-related tasks being performed in this country. This geodesic infrastructure has been affected by a series of earthquakes derived from the dynamics of plate tectonics in Chile, among them: 2010, south-central Chile, 8.8 Mw; 2014 far northern Chile, 8.2 Mw; 2015, central-northern Chile, 8.4 Mw; and 2016, Chiloe Island (southern Chile), 7.6 Mw.

The IGM, together with Chilean and international organizations, scientifically studies and analyzes the deformation of the tectonic plates over its various phases, using data from the network of permanent GNSS stations to calculate the Co-seismic and Post-seismic displacements, determining changes to the coordinates during earthquakes and the drift of the plates over the periods following the seismic movement. These differences are portrayed by means of vectors to scale, that indicate magnitude and direction of the deformation. Thus shifts are detected that range from centimeters to meters, affecting the accuracy of the SIRGAS-Chile Reference Framework, so it has been necessary to calculate coordinates referenced to the 2002.0, 2010.0, 2013.0 and 2016.0 epochs, which makes it possible to guarantee that the coordinates given to users are as accurate as possible.

*J09-4-02
Joint Symposium / J09. Geodesy and seismology general contributions

Estimation of coupling ratio on subducting plate interface and block boundary in southwest Japan using MCMC method.

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Introduction
In southwest Japan, the Philippine sea plate is subducting under the overriding plate, such as Amurian plate. The last interplate earthquakes occurred along the Nankai trough at 1944 and 1946. The recurrence interval is guessed around 90-200 years from historical earthquake. Although, it already passed over 70 years, the event did not occur yet. So, it is important to evaluate earthquake potentials for preparing huge damage due to large earthquake in near future.
In last decade, seafloor geodetic observation revealed detailed interplate coupling distribution in expected source region of Nankai trough earthquake (e.g., Yokota et al., 2016). In this study, we try to make the new block motion model based on 24 seafloor geodetic observation along the Nankai trough and 609 inland GNSS sites in southwest Japan.

Crustal block motion model
We developed crustal block motion model, including elastic plate coupling and crustal block relative motion [Kimura et al., 2017 (JpGU-AGU Joint Meeting 2017)]. At first, we make several crustal block rigid motion models, based on geological information, such as surface trace of active fault. In typically, these block motion models are too fine, because geodetic data does not have resolution for fine model based on geological information. We try to select the optimal crustal block motion model using Akaike's information criteria. After this model selection, we set the more detail of configuration, such as plate interface. In this study, we employ the algorithm for optimized number of subfaults along plate interface [Kimura et al., 2016 (126th Meeting of the Geodetic Society of Japan)].

Result
We will present the result and discussion for crustal block motions and the interplate coupling distributions in southwest Japan. Especially we focus on the defference in derived interplate coupling distribution along the Nankai trough due to the effect of coupling along Median Tectonic Line and Izu Micro Plate motion.

*J09-4-03
Joint Symposium / J09. Geodesy and seismology general contributions

EPOS-Norway - GNSS and seismological data from Norway in a common e-infrastucture

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The European Plate Observing System (EPOS) is a European project about building a pan-European infrastructure for accessing solid Earth science data. The EPOS-Norway project (EPOS-N) is a Norwegian project funded by National Research Council and is closely linked to the European EPOS project. The aims of EPOS-N project are divided into three work packages where the first one is about integrating Norwegian geoscientific data into an e-infrastructure (web portal).
There are 2 institutions in Norway providing seismological data – University of Bergen (UIB) and NORSAR, and one institution providing GNSS data - Norwegian Mapping Authority (NMA). In the presentation/poster we present the integration of the two data types into a single e-infrastructure. The first step is to standardize access to both data types and bring them into one system. The second step is to develop tools for visualization and analysis of the two different data types allowing efficient comparison of them. The EPOS-Norway project started in January 2016 and we are presenting mainly the effort we made towards the integration and ideas we want to make alive during the project.

Expanding seismic surface waves measurements towards low periods with gravity measurements

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Seismic and gravity measurements are usually considered as separate scientific problems, although both are related to the same object – the Earth. Seismometers do not measure gravity field change and seismic events in gravity measurements are considered as disturbances and are usually removed from the records. The nature of tidal gravity measurements, especially superconductive gravimeters records, allows determining very long periods of seismic surface waves. Variety of broadband seismometers allow measuring surface waves up to period of 120-150 seconds, while superconducting gravimeters record surface waves up to 400-500 seconds. This is of great importance for structure studies, because waves of longer periods make possible studying deeper structures of the Earth.
In this presentation, it has been shown how simultaneous seismic and gravity records at the same locations allow studying very long period surface waves. For test purposes 4 seismometer-gravimeter pairs have been deployed in Poland. These configurations are placed at three locations, Borowa Gora Geodetic-Geophysical Observatory (BG), Jozefoslaw Astronomical-Geodetic Observatory (JOZE), and Lamkowko Satellite Observatory (LAMK). Three seismometers are paired with two types of LaCoste&Romberg spring gravimeters (ET and model G) at all those Observatories. Additionally one seismometer is co-located on the same pillar with the iGrav-027 superconducting gravimeter at BG location. During the test period from December 2016 to January 2017 several large teleseismic events were observed with well-formed surface waves. Together with expected next events they should give dispersion curves for long surface waves, as well as periods of free oscillations. The correlation of a broadband seismometer signal with different types of gravimetric sensors gives a possibility to analyze gravimeter noise components, in the instrumental and microseismic domains.

*J09-4-06
Joint Symposium / J09. Geodesy and seismology general contributions

Sampling Frequency – the key to capturing anomalies of groundwater before earthquakes

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It is well-known that Geosciences are strongly observation-dependent. The discoveries in Geosciences also strongly rely on the development of observation techniques. Whether earthquakes can be predicted or not has been debated in several decade years, due to limited instrument recorded data aiming at precursor extraction and earthquake cycle analysis, etc. in this situation it is very important to collect observation data for precursors in widely approaches. Since 1966 Xingtai earthquake occurred in China, the observation strategy of capturing earthquake precursor for the aim of prediction has been lasted more than 40 years. Even though the precursor is debated worldwide, a complex monitoring network has been built and improved step-by-step in station configuration as well as in techniques both in instrumentation and sampling frequency, a large amount of pre-seismic anomalies have been published in a series of cases in China by seismological Press in Beijing. Here we reviewed the observation progress in sampling frequency of groundwater and its effect on the understanding process of groundwater precursors from the early stage of continuous analog recording systems to the present stage of once per minute sampling frequency of digital techniques. Through comparing the anomaly process of once per minute sampling frequency data with 50Hz sampling frequency experiment observation data in Zhouzhi well before the 2008 Wenchuan earthquake, we declaimed that the presently designed once per minute sampling frequency digital observation techniques is not enough for capturing the earthquake precursors exactly. A systematically sampling frequency technique for future digital monitoring networks of groundwater level aiming at earthquake prediction is designed and proposed based on the above research.
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*J09-5-01
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A prototype system for PPP kinematic positioning of Japanese GEONET stations

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Kinematic GNSS time series have high time resolution (typically 1~30 sec) and useful when one would like to 1) discern crustal deformations caused by successive earthquakes, and 2) detect ongoing rapid crustal deformation associated with intensive volcanic activities, to name a few. Here we developed a prototype system for kinematic positioning of Japanese GEONET stations by the precise point positioning method. This prototype is designed to generate three types of solutions, namely, ultra-rapid, rapid and final solutions depending of their latencies. Each solution will be generated 6~12 hours, 2 days and 2 weeks after data acquisition, respectively. All solutions have time resolution of 30 seconds. We evaluated the precision of the solutions in terms of coordinate repeatability and found that that of the horizontal components is typically under 1 cm for every solutions. With the solutions we may expect to etect crustal deformations caused by an earthquake at a precision of ~5 mm. We also demonstrate that these solutions are useful in monitoring long-term (~ 1year) crustal deformations. Hence we may use these solutions to model sequential short- and long-term events like an earthquake and following postseismic deformation simultaneously.

*J09-5-02
Joint Symposium / J09. Geodesy and seismology general contributions

Detection and Measurement of Land Subsidence Using InSAR and GPS in the Sabana de Bogota, Colombia, South America

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The Sabana de Bogota is located in the Eastern Cordillera of Colombia, and represents a tectonic-sedimentary basin consolidated after the final upheaval of the Northern Andes, around 5 Ma, (van der Hammen et al, 1973; Wigninga, 1996). Inside the Sabana de Bogota is located Bogota, the capital city of the country, with approximately 8 million inhabitants. Since land subsidence is a major human-induced geological hazard that affects buildings and urban infrastructure and results in severe economical consequences for both individuals and local government administrations, it is important to estimate the subsidence in the Sabana de Bogota plain using both InSAR and GPS techniques. Analysis of ALOS data acquired during 2008-2011, TERRASAR-X acquired during 2013-2015 and SENTINEL-1 acquired during 2014-2016 shows a distributed subsidence pattern, both in urban areas and agricultural areas outside Bogota city. The observed subsidence occurs most likely due to groundwater withdrawal from the local aquifer. A reprocessed height time series of GPS stations indicates that the International GNSS Services BOGT station shows a linear height trend of -44.2 ± 0.2 mm/yr (Rudenko et al., 2013). Since there was only one GPS station in the Sabana de Bogota area, (BOGT), the Colombian Geological Survey (through the Space Geodesy Research Group) installed a continuous GPS station at the El Rosal site (VROS) and built some field stations. These new sites will enable increased comparison between InSAR and GPS observations. In addition, under an agreement between the Colombian Geological Survey and the Bogota Land Cadastre Administrative Office, a network of GNSS stations has been deployed. InSAR shows subsidence up to 6-7 cm/yr while GPS stations show subsidence up to 4-5 cm/yr. We plan to continue monitoring the subsidence using GNSS and InSAR techniques and collecting water well data for analysis, in order to provide our finding to both local authorities and the public.

*J09-5-03
Joint Symposium / J09. Geodesy and seismology general contributions

Surface deformation of a mud volcano in Azerbaidzhan detected by InSAR and its source medeling

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Mud volcanoes are observed at some specific areas in the world. Mud volcano brings fluids, gasses and materials originated at a depth of several km. Understanding the dynamics of mud volcano is important in terms of a point of carbon circulation from Earth's depth to surface, its impact on greenhouse warming, disaster and so on. Mud volcano has been studied by various approaches such as geophysical exploration, structural geology, geochemical approach and so on, but geodetic observation has not been widely used. The purpose of this study is to detect surface deformation of a mud volcano in Azerbaizhan by L-band InSAR and to estimate its source modeling.
Azerbaidzhan, located on the western edge of the Caspian Sea in Central Asia, is one of the most abundant countries in term of the population of mud volcanoes over the land. We used the SAR images derived from two L-band satellites, ALOS/PALSAR and ALOS-2/PALSAR-2, launched by JAXA in 2006 and 2014 respectively. We focused on a large and unique, Ayaz-Akhtarma mud volcano. Benedetta et al. (2014) also detected the ground deformation of this mud volcano, using ENVISAT/ASAR C-band SAR data, spanning from 2003 to 2005, only along descending path; InSAR observes the surface from nearly the north to the south in a slant direction along this path. Although the ground displacement at the mud volcano was 20 cm in Line of Sight (LOS) for the two years, subsequent displacements were not clear. However, the results of our study, using ALOS data from ascending path that is opposite look direction from the previous study and ALOS-2 data for ascending and descending paths, indicated more active and larger horizontal displacements. The cumulative LOS displacement is up to nearly 300 cm for five years by ALOS and 100 cm for two years by ALOS-2. Thus we performed the source modeling to explain the displacement, assuming an elastic half-space. The modeling showed this deformation consists of normal slip and tensile opening components.

*J09-5-04
Joint Symposium / J09. Geodesy and seismology general contributions

Crustal deformation and a fault model of the 2016 central Tottori prefecture earthquake

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The Mj 6.6 inland earthquake occured on Oct. 21th, 2016 in the central Tottori prefecture, western Japan. Coseismic deformation derived from the earthquake was observed by GNSS and ALOS-2/PALSAR-2 interferometric SAR.
Continuous GNSS observation network (GEONET) is deployed in all over Japan with an average placement interval of approximately 20 km. The displacement field detected by GEONET exhibits NW-SE shortening and NE-SW lengthening around focal area, which is consistent with the focal mechanism of the earthquake. But it remains difficult to obtain detailed displacement field near focal area.
For capturing coseismic deformation of the earthquake, ALOS-2 conducted SAR observations from four different directions, ascending/descending and right-/left-looking. We succeeded in mapping three-dimensional (3-D) displacement using those InSAR data. The 3-D displacement filed shows left lateral motion along a NNW-SSE strike fault clearly.
We inverted the GNSS and InSAR data to construct a slip distribution model. Our model shows almost pure strike slip motion on NNW-SSE strike fault plane. The slip distribution model shows a maximum coseismic slip of more than 1 m at a depth of around 5 km, shallower than the epicenter. The estimated seismic moment is 2.64 x 1018 Nm (Mw6.21) from the slip distribution model.

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*J09-5-05
Joint Symposium / J09. Geodesy and seismology general contributions

Two methods of three-dimensional surface deformation field derivation with the integration of InSAR and GNSS measurements

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Geodetic measurements play an important role in monitoring crustal deformation. Interferometric synthetic aperture radar (InSAR) measurements provide high-resolution surface deformation in satellite's Line of sight direction; whereas Global Positioning System (GPS) measurements record high-precision three-dimensional surface deformation at discrete stations. These two types of measurements could be integrated to monitor crustal deformation. Here we present two methods to derive three-dimensional surface displacement field from the integration of InSAR and GPS measurements: (1) ABIC method: a unified framework based on Akaike's Bayesian Information Criterion; and (2) ESISTEM method: an extended SISTEM(Simultaneous and Integrated Strain Tensor Estimation From Geodetic and Satellite Deformation Measurements) method. The former considers smoothness among surface deformation at neighboring pixels and there is no need to interpolate GNSS measurement into the same spatial resolution as InSAR measurements, which is commonly used in previous studies, avoiding the interpolation error. The latter is based on another strategy, named SISTEM method. In SISTEM method, only surrounding GPS measurements are used as constraints based on elastic theory; while in ESISTEM method, we extend the constraints by using both surrounding GPS and InSAR measurements.
We apply the ABIC and the ESISTEM methods into the derivation of three-dimensional surface deformation field associated with the 2008 Wenchuan earthquake and the 2015 Gorkha, Nepal earthquake, respectively.

Using TerraSAR-X Interferometry and GPS to study slowly moving landslide in a vegetated terrain

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Landslide is a type of erosion processes that occurs mostly in mountainous areas, and can threaten life and cause significant damage to properties. In this regard, proper monitoring of mass movement activities using multitemporal remote sensing imagery is a crucial task for landslide hazard assessment.
As one of the most ancient and tourist cities in northern Iran, Masouleh is located in a high mountainous region. 40 percent of the whole sub-basin consists of unstable areas and mass movement appears in different forms of falls, creep and flows. In this paper we have used SqueeSAR technique using a dataset of 33 TerraSAR-X spotlight images covering a period of 18 months between June 2015 and December 2016 to investigate the kinematic of Masouleh landslide. Among different persistent scatterer interferometry techniques for deformation analysis, SqueeSAR works more efficiently in non-urban areas, which are prone to have more distributed scatterers. In addition, interferometric measurements are compared with observations from 21 GPS stations, which were collected in 3 epochs within 8 months from November 2015 to July. The maximum slope displacement velocity detected by SqueeSAR analysis is about 75 millimeters per year. InSAR loses coherence in fast moving areas which have moved about 39 cm according to GPS observations. In general, both GPS and InSAR showed similar pattern and direction of movement in the sliding slope.

*J09-6-02
Joint Symposium / J09. Geodesy and seismology general contributions

Geodetic and Seismological Risk of Operation of Nuclear Power Plants in Japan

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The national project of earthquake prediction started on 1965 in Japan. Most prospective approach for short term predictions was considered to be continuous monitoring of crustal deformations. This idea was based on observational results of Sassa and Nishimura (Kyoto University). They first reported that anomalous tilt change with the order of 0.1" was observed at the Ikuno mine located 60km away from the epicenter of the 1943 Tottori eq. of M7.2. Since then, reliable anomalous tilt or strain changes were not reported. Destructive earthquake of M7.3 occurred around Kobe city on 17 January 1995. Using a precise laser strainmeter, we had been carried out strain measurement at the Rokko-Takao station in Kobe. The station was existing just above the fault plane of the earthquake. We could not find any anomalous strain changes before the earthquake. This fact indicates that precise observations using tiltmeters and strainmeters are not effective tools for short term predictions of earthquakes. It is abnormal worldwide that more than 50 nuclear power plant units were installed in Japan. The Fukushima 1st nuclear plant suffered catastrophic damage due to the 2011 off the Pacific coast of Tohoku Eq. (Mw9.0). It is estimated that about 1% of total radioactive substances were released into the atmosphere during one week from March 11, 2011, and 99% of radioactive substances are remaining in the vessels of reactors as the form of nuclear fuel debris. In near future, we must consider the possibility of the outbreak of the earthquake that Fukushima will be shaken by strength of seismic intensity of 7 or 6. We must consider the Geodetic and Seismological Risk of Operation of Nuclear Power Plants, not only the Fukushima 1st Nuclear Power Station but also all Nuclear Power Stations in Japan.

*J09-6-04
Joint Symposium / J09. Geodesy and seismology general contributions

Gorkha, Nepal Earthquake 2015 – Causes, Consequences, Socio- Economic Impacts, Lessons Learned and Way Forward

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Nepal is prone to various types of disasters such as: earthquakes, floods, landslides, fires, epidemics, avalanches, windstorms, hailstorms, lightning, glacier lake outburst floods, droughts and extreme weather events. Among all these disasters – earthquake is the most scary and damaging. The effects of a disaster, whether natural or human induced, are often far reaching. In addition to the natural factors, the losses from disasters are increasing due to the human activities and absence of proactive legislation. Fundamentally, the weak structures have been found as the major cause of infrastructure collapse in earthquakes. This emphasizes the need for strict compliance of town planning bye-laws and earthquake resistant building codes. Thus, proactive disaster management legislation focusing on disaster preparedness is necessary. This paper analyses the critical gaps responsible for emphasizing the seismic risk and of factors that would contribute towards seismic risk reduction to enable various stakeholders to address the critical areas for improving seismic safety in Nepal and other earthquake prone countries. Additionally, this paper aims to pinpoint the deficiencies in disaster management system in Nepal with reference to the devastating earthquake of 25 April 2015 and suggest appropriate policy and advanced technical measures.

*J09-P-01
Joint Symposium / J09. Geodesy and seismology general contributions

InSAR analysis all over Japan by ALOS-2 (Daichi-2) / PALSAR-2 data

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SAR interferometry (InSAR) is a powerful and unique remote sensing technique for detecting and monitoring ground surface deformation with high spatial resolution without any ground based observation infrastructures.
The Geospatial Information Authority of Japan (GSI) has conducted to monitor ground surface deformation of earthquakes, volcanic activities, subsidence and landslides throughout Japan by InSAR analysis using ALOS-2 data. With images obtained from InSAR analysis (hereinafter referred to as “SAR interferograms"), we have detected a lot of ground surface deformations caused by earthquakes and volcanic activities, subsidence derived from overuse of ground water, seasonal uplift and subsidence in snow zones caused by snow melting, subsidence in landfills and phase variations assumed to be caused by slope deformation.
SAR interferograms are formatted into tile data and can be browsed on a web map of GSI, "GSI Maps". GSI Maps enables us to superimpose SAR interferograms on various geospatial information provided by GSI such as topographic maps, aerial photographs, volcanic land condition maps and so on. This visualization enables us to easily compare SAR interferograms to other information like topography and geology and more robustly identify an area of ground surface deformations on the SAR interferograms.
We report SAR interferograms of ALOS-2, which are routinely covering all over Japan, and also challenges on InSAR analysis and system in the paper.

*J09-P-02
Joint Symposium / J09. Geodesy and seismology general contributions

EPOS-Norway – Integration of Norwegian geoscientific data into a common e-infrastructure

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The European Plate Observing System (EPOS) is a European project about building a pan-European infrastructure for accessing solid Earth science data. The EPOS-Norway project (EPOS-N) is a Norwegian project funded by National Research Council and is closely linked to the European EPOS project. The aims of EPOS-N project are divided into three work packages where the first one is about integrating Norwegian geoscientific data into an e-infrastructure (web portal). The other two work packages are about improving the geoscientific monitoring in the Arctic and about creating a Solid Earth Science Forum to communicate the progress within the geoscientific community and also providing feedback to the development group of the e-infrastructure. There are 5 institutions in Norway actively participating and providing data in the EPOS-N project – University of Bergen (UIB), University of Oslo (UIO), National Mapping Authority (NMA), Geological Survey of Norway (NGU) and NORSAR. The data which are about to be integrated are divided into categories – seismology, geodesy, geological maps and geophysical data. Before the data will be integrated into the e-infrastructure their formats need to follow the international standards which were already developed by the communities of geoscientists. Also, description of the data, i.e. metadata, needs to be clarified and recognized within the CERIF database system. For now, there are 33 Data, Data Products, Software and Services (DDSS) described in EPOS-N list. In the poster we present the Norwegian approach to the integration of the geoscientific data into the e-infrastructure, closely following the European EPOS project development. The partner in the project - Christian Michelsen Research (CMR) is specialized in visualizations of data and developing of an interactive web portal allowing to users making workflows (using Jupyter Notebook). One of the main challenges is to integrate the various data and bring them to a single environment.

*J09-P-03
Joint Symposium / J09. Geodesy and seismology general contributions

Comparison of Superconducting and Spring Gravimeters at the Mizusawa VLBI Observatory of the National Astronomical Observatory of Japan

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Continuous microgravity monitoring is utilized to gain new insights into changes in the subsurface distribution of magma and/or fluid that commonly occur beneath active volcanoes. Rather new superconducting and spring gravimeters, iGrav#003 and gPhone#136 are collocated with a superconducting gravimeter, TT#70 at the Mizusawa VLBI Observatory of the National Astronomical Observatory of Japan, since the end of September, 2016 in order to evaluate those performances before field deployment planned in 2017.
Calibration of iGrav#003 was carried out by collocation with an absolute gravimeter FG5 of the Earthquake Research Institute, University of Tokyo (Okubo, 2016, personal comm.) at a Fundamental Gravity Station in Sendai in July, 2016. Based on the scale factors of iGrav#003 obtained by the calibration and of gPhone#136 provided by the manufacturer (Micro-g LaCoste, Inc.), tidal analyses are performed by means of BAYTAP-G (Tamura et al., 1991, GJI). Amplitudes and phases of each major tidal constituent mutually agree well within ±4 % and ±3 degrees, respectively.
The instrumental drift rate of iGrav#003 is very low, about 5 micro-Gal/month, whereas that of gPhone#136 is very high, about 500 micro-Gal/month. The high drift rate of gPhone#136, however, is well approximated by a quadratic function at present and can be removed. The detrended time series of gPhone#136 shows good agreement with iGrav#003 time series in the overall feature: gravity fluctuations with amplitudes of about a few micro-Gal and with durations of a few days, which may be due to variations in the moisture content of the topmost unsaturated sedimentary layer and the water table height. It suggests that both instruments may capture volcanic signals associated with pressure changes in magma chambers, dike intrusion/withdrawing, and so on.

*J09-P-04
Joint Symposium / J09. Geodesy and seismology general contributions

Exponential pore pressure/groundwater level changes associated with the 2016 Kumamoto Earthquake (Mj7.3) observed at Tono region, central Japan

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Clear exponential pore pressure/groundwater level changes associated with the 2016 Kumamoto Earthquake (Mj7.3) were observed at borehole observation sites "STG200 and STG200N" in Mizunami Underground Research Laboratory (MIU), and TGR350 borehole observation site located approximately 500m south of MIU, in the Tono region, central Japan (Hypocentral Distances are approximately 665km). These observation sites are located approximately 3 km southeast of 16 closely clustered well where were observed co-seismic groundwater level/pressure changes (King et al, 1999; JGR).
Amount of pore pressure changes in STG200 and STG200N are 30 and 28 kPa-rise, respectively, and groundwater level in TGR350 is 2.3m-rise. At the STG200N site, continuous in-situ stress recorded by the borehole stress meter (Ishii and Asai, 2013; EPS). In order to recognize the relationship between the co-seismic pore pressure changes and the seismic waves, we compared the 20 Hz sampling pore pressure and stress records before and after the occurrence of 2016 Kumamoto Earthquake (Mj7.3). As the result, pore pressures begin to increase just after the maximum amplitude of seismic waves (dynamic stress variations) passed through our site.
We will present the details of these pore pressure/groundwater level changes, and attempt to clarify the qualitative/quantitative model for the co-seismic pore pressure/groundwater level changes.

*J09-P-05
Joint Symposium / J09. Geodesy and seismology general contributions

A possible mechanism of Omori-Utsu'slawthroughan example of the great Tangshan earthquake

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We propose a conceptual model of earthquake source body with Kelvin viscoelastic property to investigate the physical mechanism of Omori-Utsu's law. Supposing that tectonic stress field after main shock does not change with time and equivalent viscosity in the aftershock region is much lower than that of its outside in the period of total aftershock activity. This model can simulate aftershock sequence induced by post-seismic creep and stress readjustment, and the whole process including creep stopping, materials recovering to its elastic state, and faulting turning to stick state for next earthquake. Finite element method is used to calculate stress field evolution caused by a main shock and its aftershocks in the model with heterogeneous material properties. Furthermore, the model and the method is used to simulate decay of the aftershock frequency of the 1976 Tangshan MS7.8 earthquake. The results show that the mechanism of Omori-Utsu's law may be attributed to the stress changes caused by the creep of the fault and earthquake source body, which implies that aftershock frequency depends on the creep rate and decay time of the aftershocks is controlled by the equivalent viscosity. The lager the viscosity is, the longer the creep time or the aftershocks last.

*J09-P-06
Joint Symposium / J09. Geodesy and seismology general contributions

Updating Hypocenter Location around Indonesia Region Derived from 3D Seismic Velocity Structure: Time Period of April 2009-July 2016

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We conducted hypocenter relocation of ˜40,000 events (Magnitude of 1.4 to 8.5) recorded by 451 stations around and outside Indonesia region that compiled by Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG) from April 2009 to July 2016. We used teleseismic double-difference relocation inversion including local, regional and teleseismic arrival time data. Our previous study of 3D seismic velocity model beneath the Indonesian region with grid size 1o by 1o and the 1D seismic velocity model were used for the regions inside and outside Indonesia region, respectively. This method improved limitation from BMKG earthquake data catalog in which events were recorded from scattered seismic station array and insufficient azimuthal gap around Indonesia. Our results show that travel-time RMS residuals were greatly reduced compared to those of the BMKG catalog. Seismicity at shallower depth (less than 50 km) shows significant improvement, refining shallow geological structures, e.g. trench and major strike slip faults. Clustered seismicity is also detected beneath volcanic regions, and probably related to volcano activities and also major faults nearby. Beneath Western Sunda arc, Wadati-Benioff Zone (WBZ) extents to 300 km and it depicts gently dipping slab beneath this region. The WBZ beneath Eastern Sunda Arc is extent deeper to 500 km and depicts steep slab geometry. At Sunda-Banda transition zone, we found anomalously low seismicity beneath oceanic-continental transition region. WBZ of highly curvature Banda arc extents to 600 km and depicts two-slab model. In Molucca collision zone, seismicity from this region clearly shows two-slab of Halmahera plate: east- and west-dipping slab. Furthermore, we used global centroid moment tensor catalog where data available for earthquakes with magnitude 6 or greater. Mostly, focal mechanism solution for large earthquakes around this region are thrust mechanism that related to subduction processes.

*J09-P-07
Joint Symposium / J09. Geodesy and seismology general contributions

Aftershock Observation of Mw 6.5 Pidie Jaya, Aceh, Indonesia Earthquake: Preliminary Results

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The Mw 6.5 Pidie-Jaya, Aceh, Indonesia earthquake occurred on December 7, 2006. This destructive event causing many victims, houses and infrastructure collapses as reported by the authority. The previous geological and geophysical studies did not show the fault surface indication around the mainshock, so it is very important to investigate the fault plane and source mechanism of the event. A week after, we deployed 9 seismometers to observed the aftershock distriburion. We carrefully picked P-and S-arrival time of the small event and then determined the hypocenter location. In total, we determined ~320 event for one month monitoring. Our preliminary results show the aftershocks location have striking of NE-SW direction with the focus depth of 10 to 30 km. These events cluster also appear perpendicular to the main Sumatra fault, so it is antithetic fault likely. The comparison with geological and geodetical studies are needed to get much better interpretation.

Keywords: Pidie-Jaya, earthquake, aftershock

*J09-P-08
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Estimation of the seismic-motion-generated changes in permeability structure nearby a fault fracture zone by means of a groundwater migration model

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We report that permeability structure in a fault fracture zone can be changed every time strong seismic motions occur due to great earthquakes, even though the fault itself is not the seismic one.
Groundwater can easily migrate in a fault fracture zone with higher permeability. The permeability is expected to vary due to crustal stress, alteration of the crust and so on. In fact, permeability in the crust nearby Nojima fault, which was one of the seismic faults for the 1995 Hyogo-ken Nanbu earthquake, was reported to have been reduced gradually after the earthquake (Mukai and Fujimori, 2007). It is considered to reflect the recovery process of the fault.
We have continuously observed groundwater discharge and pore pressure as well as crustal movements at Rokko-Takao station in the western Japan. This station was established in a tunnel across Manpukuji fault. The groundwater discharge and the pore pressure had increased just after some great earthquakes apart from this station. A part of these changes was considered to be caused by permeability changes in the fracture zone, which might result from the outflow of mud due to the strong seismic motions.
We had made a groundwater migration model with homogeneous permeability structure to estimate permeability change (Mukai et al., 2016). We applied the observational data of groundwater discharge and pore pressure to the model and could estimate permeability change just after the 2011 off the Pacific coast of Tohoku Earthquake. In this study, we modified the model as considering the effect of heterogeneous permeability structure, and tried to estimate permeability changes due to some great earthquakes such as the 2016 Kumamoto earthquake. We report the characteristics of the permeability changes and a possible mechanism to cause such changes in consideration of the observed crustal movements which were affected by groundwater migration.

*J09-P-09
Joint Symposium / J09. Geodesy and seismology general contributions

INTAROS – INTEGRATED ARCTIC OBSERVATION SYSTEM

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By DEC 1st 2016 the five year INTAROS project was launched with Horizon 2020 funding from the European Commission. The overall objective of INTAROS is to develop an integrated Arctic Observation System (iAOS) by extending, improving and unifying existing systems in the different regions of the Arctic. INTAROS will have a strong multidisciplinary focus, with tools for integration of data from atmosphere, ocean, cryosphere and terrestrial sciences, provided by institutions in Europe, North America and Asia. Satellite earth observation data plays an increasingly important role in such observing systems, because the amount of EO data for observing the global climate and environment grows year by year. In situ observing systems are much more limited due to logistical constraints and cost limitations. The sparseness of in situ data is therefore the largest gap in the overall observing system. INTAROS will assess strengths and weaknesses of existing observing systems and contribute with innovative solutions to fill some of the critical gaps in the in situ observing network. INTAROS will combine many scientific disciplines of which both seismology and geodesy are included. The seismological component of INTAROS includes e.g. a reviewed catalogue of the earthquakes activity in the Arctic, to find the areas that are poorly observed and to perform a yearlong deployment of broadband OBS'es in the Arctic using ROV technology, to show how to fill the earthquake/seismic monitoring gap in the Arctic Ocean. The geodetic component of INTAROS includes e.g. that sea level information from tide gauges and from satellite altimetry (also Sentinel-3) will be combined to obtain sea level anomalies and associated geostrophic ocean currents and provide new estimations of ice sheet mass balance and changes using GNSS/GPS data and development of new methods to improve these estimations. We will give an overall presentation of INTAROS and outline the seismological and geodetic contributions.

*J09-P-10
Joint Symposium / J09. Geodesy and seismology general contributions

Simulation of Hayabusa2 crossover orbit analysis using laser altimeter data

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The asteroid explorer “Hayabusa2" was launched in 2014, and will arrive the target C-type asteroid, Ryugu in the middle of 2018. Hayabusa2 will stay there for one and a half years, and perform exploration with small rover and lander, sample acquisition from Ryugu's surface, and various remote-sensing observations. In the mission, in order to estimate Hayabusa2 orbit and Ryugu's geodetic parameters as precise as possible, crossover orbit analysis using laser altimeter (LIDAR) between Hayabusa2 and Ryugu is planned, in addition to conventional radiometric tracking data analysis.
In this study, as a preparation for actual data analysis, we simulated Hayabusa2 orbit analysis in offline. We developed a simulation program for Hayabusa2 orbit analysis, including crossover orbit analysis. Test data of Hayabusa2 orbit, Ryugu ephemeris, and Ryugu shape model were also created for the simulation. The orbit analysis was simulated in the following order: 1) Hayabusa2 orbit determination with range and range rate observations from ground tracking stations to Hayabusa2, 2) Determination of Hayabusa2 orbit with respect to Ryugu center by crossover orbit analysis using LIDAR-observed ranges between Hayabusa2 and Ryugu, 3) improvement of Ryugu ephemeris using 1) and 2) results, 4) improvement of Hayabusa2 orbit by performing 1) again with updated Ryugu ephemeris, and 5) iteration of 1) to 4). We discuss how much the precision of determined Hayabusa2 orbit changes by changing error magnitudes of each observations and Ryugu ephemeris.

*S01-1-01
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Automatic hypocenter determination for the Seismological Bulletin of Japan using Bayesian estimation and its applications

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A quick estimation of spatial and temporal hypocenter distributions in swarms and aftershocks is essential for estimating the source geometry and possible damaged area. The automatic hypocenter determination method is important to understand seismic activities in real time. We developed a new method using Bayesian estimation to identify multiple concurrent earthquakes to be used for the Seismological Bulletin of Japan. This method makes integrated use of P- and S-wave arrival times and maximum amplitude. We applied this method to earthquakes in the vicinity of Japan. The ratio of detected earthquakes compared with those in the manually checked event list is almost 100% (M>=1.0) at inland and shallow areas. At offshore or deep areas, it is about 80% (M>=1.0). We also applied this method to the aftershock activity of the northern Nagano Prefecture on November 22, 2014. In this case, this method could detect more than 1,700 events in 24 hours, although the previous automatic determination system could detect only 250 events at that time. This indicates that our method is useful to understand seismic activities in real time. The new seismic monitoring system using this method have started its operation at the Japan Meteorological Agency in April 2016. In the 2016 Kumamoto earthquake, which began on April 14, the ability of the method was fully demonstrated. By the end of May, number of hypocenter determinations reached about 70,000, which was far more than the level possible by manual processing, and the system played an important role to grasp the spatio-temporal characteristics of the activity.

*S01-1-02
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Automated seismic event location combining waveform stacking and relative location techniques

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Microseismic monitoring became a common operation in many applications (e. g. induced seismicity). The analysis of microseismic data is challenging, because of the large number of recorded events often characterized by low signal-to-noise ratio. In the last years, to improve the performance of the automated location procedures, various waveform based methods for microseismicity characterization have been proposed. These picking-free methods exploits the coherence of the waveforms recorded at different stations and appear to be more noise robust than the traditional methods (based on automatic phase picking). However, like any other absolute location method, the accuracy strongly depends on the knowledge of the velocity model. The use of simplified 1D velocity models in areas characterized by complex 3D velocity structures or by pronounced topography may strongly affect the locations accuracy. The poor knowledge of the velocity model is, in fact, the largest source of error in the seismic event location process. In this work we present a location method which combines features of relative location techniques with the waveform based location methods. This approach inherits all the advantages of the fullwaveform location methods without its main drawback (i.e. effect of poorly known velocity model). In fact, this method is less dependent on the knowledge of the velocity model, improving the location accuracy: 1) it accounts for phase delays due to local site effects, e.g. surface topography or variable sediment thickness 2) theoretical velocity model are only used to estimate travel time within the source volume, and not along the entire source-sensor path. In order to validate this approach we tested it with different synthetic and real datasets, including induced seismicity related to geothermal energy exploitation in St. Gallen (Switzerland) and seismic swarms of volcanic origin in Nicaragua.

*S01-1-03
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S01. Open session

Over 20 years of HYPOSAT: Newest developments

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About 20 years ago, the first versions of HYPOSAT, a free software package to locate seismic events at local, regional and teleseismic distances were developed and presented (Schweitzer, 1997). In 2001, a paper was published describing the principal features of the program package and the software package was officially released (Schweitzer, 2001). Later, a detailed manual became part of the IASPEI New Manual of Seismological Observatory Practice (Schweitzer, 2002).
During the last decade, many new features steering the inversion process and correcting for effects that can influence seismic travel times were implemented in HYPOSAT and many options to handle input and output data were included. Today's program version can run on Unix and Linux platforms.
The program package has been used by many researchers worldwide. These users have helped to improve the software by reporting problematic results and bugs and requested additional input / output options.
In this talk an overview will be presented over the principal ideas behind HYPOSAT. Additionally, many of the recently implemented features will be explained and discussed.

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*S01-1-04
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

A tremor location method using products of cross correlations

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We introduce a back-projection method to locate tremor sources using products of cross-correlation envelopes of signals between seismic stations. Tremor is characterized by signals which lack a clear onset. For such signals it is usually not possible to use first-arrival picks to locate a source. Instead, inter-station cross-correlation is commonly used for this purpose. We introduce a method which resembles high-order cross-correlations, but it is much less computationally expensive. In this method we calculate up to the (n-1)th-order products of cross-correlation envelopes for a given subset of n stations. The products are back projected to hypothetical source locations in a geographic grid and the resulting maps are stacked over combinations of station subsets. We show that compared to existing correlation methods and for realistic signals and noise characteristics this way of combining phase information can significantly suppress the effects of correlated and uncorrelated noise and therefore give a robust estimate of source locations. We present synthetic examples which demonstrate the robustness of the method and apply the method to tremor at Katla volcano, Iceland in 2011.

*S01-1-05
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Rapid estimation of seismic moment, magnitude and energy for small to large events: improvement from Central Italy, 2016 seismic sequence

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The implementation of techniques that are able to determine the characteristics of a given event in near real time is essential for seismology and is of enormous importance to deal with the seismic emergency as quickly and accurately as possible. The SeisRaM (Seismological Research and Monitoring) Group of the Department of Mathematics and Geosciences of the University of Trieste is concerned to the seismic monitoring in real time of the Italian territory. Techniques and procedures have been developed for the accurate determination of source parameters that are computed within few minutes after the earthquakes and rapidly revised. A long collaboration with a National Civil Protection leads to improve the quality of the results and to optimize such procedures for civil defense purpose. The recent seismic sequence, occurred in the intra-Apennine extensional fault system of Central Italy, gave the opportunity to further test the near real time system. In fact, records from the seismic sequence following the Amatrice earthquake of 2016, 24 August (Lavecchia et al, 2016), are analyzed using an automated routine to determine moment magnitudes and strong motion parameters. Seismic moment and the corresponding moment magnitude are obtained from the spectrum of far-field body waves (Gallo et al, 2014), as well as radiated energy, the Brune stress drop and apparent stress. The application of the automated algorithm in near real time provides important insight into the ground motion characteristic to obtain a rapid characterization of seismic source parameters in case of a strong event, for research, engineering purposes and emergency services.

*S01-1-06
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S01. Open session

Towards routine determinations of earthquake focal mechanisms obtained from P-wave first motion polarities

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We investigate the possibility to calculate earthquake focal mechanisms in a routine and systematic way based on P-wave first motion polarities. We use any available parametric data in the ISC database. We also use ISC auto-picked polarities from waveform data up to teleseismic epicentral distances (up to 90 degrees) for stations in the international registry that are not reported to the ISC. A bi-product of our study can potentially be an additional set of picked polarities and direct P-wave teleseismic arrival times, and/or the identification of stations associated with polarity reversals. We use the HASH algorithm for the determination of the earthquake mechanisms as it provides an elegant way to take into account uncertainties in earthquake location and Earth's structure. We slightly modified the algorithm to deal with a wide range of epicentral distances and to take into account the ellipsoids that define the ISC location errors. We first carry out benchmark tests for a set of ISC reviewed earthquakes (mb > 4.5). We use the HASH classification to define the mechanism quality and we find that the mechanisms of quality A, B, and C with an azimuthal gap up to 90 degrees are well compared to our benchmark mechanisms. Nevertheless, the majority of our mechanisms fall into class D as a result of limited polarity data from stations in local/regional epicentral distances. Specifically, we compute the minimum rotation angle between our mechanisms and the benchmarks and we find 24% of D cases with a rotation angle up to 35 degrees and azimuthal gap up to 120 degrees. We finally specify selection criteria with respect to the stations' distribution, misfit and nodal plane uncertainties in order to separate the trusted mechanisms from the rest.

*S01-2-01
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S01. Open session

Calculating the ISC's own magnitudes

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The International Seismological Centre (ISC) routinely reports body and surface wave magnitudes for earthquakes recorded at teleseismic distances. Current ISC procedures for calculating magnitudes rely on amplitude-period pairs reported to the ISC by contributing agencies. Here, we develop a new method to calculate magnitudes in house at the ISC, in accordance with the IASPEI standards outlined by the IASPEI/COSOI Working Group on Magnitudes. These new ISC magnitudes are calculated using waveforms downloaded from international data centres (IRIS, EIDA, GeoNet) and our own automatic algorithms for measuring amplitude (A) and period (T). We present results for broadband body wave magnitudes (mB(BB)) calculated using the relation mB(BB) = log10((A/T)max) + Q(d,h), where Q(d,h) is the attenuation function for P-waves recorded on vertical component seismographs, established by Gutenberg and Richter (1956), at epicentral distances d and for a focal depth h, and (A/T)max = (Vmax/2pi), where Vmax is the ground velocity associated with the maximum velocity trace-amplitude in the entire P-wave train (Bormann and Saul, 2008). We use a dataset of recordings of up to 1000 earthquakes of magnitude greater than 5 in the period 2012 – 2013, that are reviewed in the ISC Bulletin. We compare our own ISC mB(BB) with MW from GCMT, mb from NEIC, and conventional ISC mb and MS. These new ISC-calculated magnitudes will be an extra dataset available to users of the ISC Bulletin, and will provide a robust measure of magnitude that is in agreement with IASPEI standards. To complement the existing amplitude and period measurements reported to the ISC by contributing agencies, ISC-picked amplitude and period measurements and their associated amplitude-phase arrival time will also be reported and made available to users.

References:

Bormann, P., J. Saul (2008): The New IASPEI Standard Broadband Magnitude mB. Seismological Research Letters, 79, 5, p. 698-706.

*S01-2-02
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S01. Open session

Policy issues for the European Seismological Services within EPOS

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In the framework of EPOS, the European Plate Observing System initiative, which aims to become a European Research Infrastructure Consortium (ERIC) covering the Solid Earth Sciences,the European seismological community is further developing its portfolio of common European services for seismological data and products, as one of the domain specific EPOS Thematic Core Services. Efforts are focusing on technical innovation, harmonization and coordination, building upon decades of collaboration in the collection and dissemination of earthquake parameter information at the European-Mediterranean Seismological Centre (EMSC), of seismological waveforms and associated information at the Observatories and Research Facilities for Seismology in Europe (ORFEUS), as well as on more than 10 years of mainly project-driven collaboration in seismic hazard assessment leading to the establishment of the European Facilities for Earthquake Hazard and Risk (EFEHR). One key aspect in EPOS-Seismology is the conscious and comprehensive addressing of non-scientific issues: Data (sharing) policies, licenses and intellectual property (including attribution issues), and data management planning and implementation. A major challenge is the harmonization between developments and ideas in EPOS, established practices within the European level seismological institutions, and national / institutional policies (where and if existent), recognizing that e.g. ORFEUS and EMSC have each more than 50 participating member institutions from more than 30 countries.

In this contribution we will review the state of the discussion on these issues, present current strategies and plans regarding policy harmonization and implementation, and also address connections of our efforts to other relevant initiatives originating for example from GEO or RDA.

*S01-2-03
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S01. Open session

The Mexican National Seismological Service: An overview

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The Servicio Sismologico Nacional (SSN, Mexican National Seismological Service) has a history of 107 years. In the last 10 years, it has gone through an important modernization process, which has involved the installation of new broadband stations; co-localization of GPS receivers with the velocity and acceleration sensors; collaboration with other Mexican networks to increase the number of stations from which it receives data; migration to larger and faster acquisition, processing and storing systems; and a new building that hosts the central facilities. 2017 marks the beginning of a new period of the SSN, since a significant increase on the number of stations and computer capabilities will be part of a new project. On this work, we will present an evaluation of the current performance of the network, the communication and system architecture, as well as monitoring and reporting processes, which include the use of social networks and a mobile app; this towards the optimal design of the upcoming improvements.

*S01-2-04
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Compilation of a Seismic Bulletin for the European Arctic

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During the years 2014 - 2016, a joint Norwegian-Russian project between the three partners NORSAR in Kjeller, Norway, the Federal Center for Integrated Arctic Research of the Ural Branch of RAS in Arkhangelsk and the Kola Branch of the Geophysical Survey of RAS in Apatity, was jointly financed by Norwegian and Russian research agencies. One task of this project was to compile a joint seismic bulletin for the European Arctic for the last decades. The main sources for this new bulletin were the data collected at the International Seismological Centre (ISC), the analyst reviewed bulletins of NORSAR and the two Russian project partners, the bulletins of the IDC in Vienna and its forerunners, the Nordic Bulletin compiled at the University of Helsinki, and the bulletins collected at the University of Bergen. In addition, seismic onsets from permanent and temporary stations read at NORSAR within different projects as e.g., during the IPY, were added to the new bulletin compilation.
The greatest challenge for this new unified bulletin is removing all the onset readings from different agencies analyzing the same seismic stations: due to international data exchange, data from the permanent stations in the European Arctic are in between analyzed by five or more institutions and then reported into the international databases. These institutes are not only processing the data differently, but they may even use different rules to name the seismic onsets.
All these data entries have to be homogenized, to achieve a unified bulletin. The new bulletin contains the most complete collection of seismic events observed in the European Arctic north of latitude 70 degrees for the time period 1990 to autumn 2015.

*S01-2-05
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

The ISC-GEM Global Instrumental Earthquake Catalogue: Current status and efforts to extend the period 1904-1919

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The first version of the ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009) (www.isc.ac.uk/iscgem/index.php) was released in January 2013 (Storchak et., 2013) after a 27-month project co-funded by the GEM Foundation. The catalogue was required to reassess the homogeneity (to the largest extent possible over time) of the earthquake parameters (especially location and magnitude) and list them along with formal uncertainties to facilitate seismic hazard and Earth's seismicity studies.
The first release included earthquakes selected according to the following time-variable cut-off magnitudes: Ms=7.5 before 1918; Ms=6.25 during 1918-1963; and Ms=5.5 from 1964 onwards. Because of the importance of having a reliable seismic input for seismic hazard studies, funding from USGS, NSF, GEM and a few commercial companies in the US, UK and Japan allowed us to start working on the extension of the ISC-GEM catalogue both for earthquakes that occurred after 2009 and historical earthquakes listed in the International Seismological Summary (ISS), which fell below the original ISC-GEM cut-off magnitude of 6.25 before 1964. This is a four-year project that aims to add as many earthquakes as possible that occurred between 1904 and 1959. In this contribution we present the updated ISC-GEM catalogue at the end of the third year extension program (Version 4.0), which includes over 2,000 more earthquakes during 2010-2013 and thousands more between 1920 and 1963 as compared to the first version. We also discuss the current work to include as many earthquakes as possible during 1904-1919. The extension of the ISC-GEM catalogue will be useful to regional seismic hazard studies because the ISC-GEM catalogue can serve as basis for cross-checking location and magnitude of those earthquakes listed both in global and regional catalogues.

*S01-2-06
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S01. Open session

Development of a web-application system for seismic waveform data observed at real-time with the seafloor seismic network, DONET

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It is well-known that devastating earthquakes have struck the Southwest coast of the Japanese Islands repeatedly in the past. Of these earthquakes, those that occurred in the Nankai Trough region are very significant, because they have caused extreme hazards in these coastal areas due to large tsunamis. In order to detect tsunamis in the earthquake source areas, JAMSTEC deployed the seafloor seismic network, DONET in 2010. The DONET system consists of an array of 20 stations in total, each of which are composed of multiple types of sensors, including strong-motion seismometers and quartz pressure gauges. We have developed a web application system, REIS (Real-time Earthquake Information System) that provides seismic waveform data to some local governments close to the Nankai Trough. The main purpose of REIS is to inform local government officers as to what has actually occurred in the Nankai trough region when there is a large earthquake. REIS itself is not designed to issue early tsunami warnings, but it should be useful for local government officers to get every possible piece of information to quickly assess large earthquakes. We have ensured that the display of real-time waveform data from DONET is performed with a maximum delay time of approximately 2 seconds. This delay time is considered appropriate to allow local government officers to promptly identify current seismic activity around Nankai Trough region. In 2016, the network has been enlarged to the west of DONET and about 30 new stations, DONET2, are added to the network. We have renovated the REIS system so that it may handle additional seismic waveform data without any problems. Also, since April 2016, the ownership of DONET has officially transferred to the National Research Institute for Earth Science and Disaster Prevention (NIED). JAMSTEC has a contract for the operation of DONET with NIED and will keep the operation of REIS and event data system as it is.

*S01-3-01
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S01. Open session

The Global Seismographic Network (GSN): New VBB Borehole Sensors, Sensor Emplacement Techniques and Data Quality Assessment using MUSTANG

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The Global Seismographic Network (GSN) is a 152 station, globally-distributed, permanent network of high quality seismological and geophysical sensors. The central design goal of the GSN is "to record with full fidelity and bandwidth all seismic signals above the Earth noise, accompanied by some efforts to reduce Earth noise by deployment strategies". After over 20 years of operation, most of the network's technical design goals have been met. The challenge is to continue to modernize the network and maintain high data quality in an era of flat or declining budgets.

We will present a number of approaches to maintain GSN data quality and improve overall network noise performance. These include: 1) Standardizing equipment across the network, e.g. deploying new Quanterra Q330HR dataloggers; 2) Developing next-generation very broadband borehole sensors to replace the failing KS-54000 sensors (one third of the network); 3) Using the results of noise analyses to determine where new sensor emplacement techniques, e.g. shallow boreholes, might achieve lower noise performance for the existing site conditions. We also show how shallow borehole installations may be adapted to vaults (which make up two thirds of the network), as a means of reducing tilt-induced signals on the horizontal components.

The GSN is creating a prioritized list of proposed infrastructure and equipment upgrades at selected stations with the ultimate goal of optimizing overall network data availability and noise performance. For this effort, we are utilizing data quality metrics and Probability Density Functions (PDFs)) generated by the IRIS Data Management Centers' (DMC) MUSTANG (Modular Utility for Statistical Knowledge Gathering) tool. We will present our MUSTANG metric analysis and show GSN sites which could benefit the most from instrumentation and infrastructure upgrades.

*S01-3-02
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Anatomy of a subduction zone – seismicity structure of the northern Chilean forearc from >100,000 relocated earthquake hypocenters

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We present a catalog of >100k well-located earthquake hypocenters for the northern Chilean forearc region, between the latitudes of 18.5 deg. S and 24 deg. S. The events span the period between 2007-2014 and were extracted from the Integrated Plate boundary Observatory Chile (IPOC) permanent station network dataset. Using this new, high-resolution set of hypocenters, we can outline the slab structure in unprecedented detail, including slab topography or the resolution of structures inside the zone of intermediate-depth seismicity. For the compilation of the catalog, we relied on an automated multi-step process for event detection, association and phase picking. The earthquake hypocenters were then relocated in a 2.5D velocity model for the Northern Chile forearc with a probabilistic approach allowing uncertainty estimation. In a final step, double-difference relocation incorporating cross-correlation based phase lag times was performed, which further sharpened event clusters. The majority of all >100k earthquakes are located at intermediate depths (80 and 140 km) inside the subducted slab. This area of pervasive activity extends along the entire strike of the investigated area, but shows a clear offset at 21 deg. S, which may hint at a slab tear at this location. Further updip, a triple seismic zone at depths between 40 and around 80 km is visible, which grades into the highly active event cluster at intermediate depths: below the plate interface, which is clearly delineated by seismic activity, a second parallel band of hypocenters only about 5 km below likely corresponds to earthquakes occurring within the oceanic crust or close to the oceanic Moho. A third band of earthquakes, paralleling the other two at about 20-25 km below the interface, clearly indicates the presence of seismicity in the oceanic lithospheric mantle. Seismicity in the upper plate is pervasive through the entire crustal thickness near the coast but gets shallower towards the volcanic arc.

*S01-3-03
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

The 30 May 2015 Bonin Deep Earthquake and the 660-km Discontinuity Around its Source Region

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The 30 May 2015 Bonin deep earthquake occurred near the bottom of the mantle transition zone (depth 664 km, Mw 7.8; USGS), and its seismic waves traversed the mantle to many broadband stations in a distance range that may be affected by the 660-km discontinuity in and around the source region. Our results from finite-fault inversion with the P and SH waveforms and observations of aftershock waveforms suggest that a significant, subhorizontal 660-km discontinuity could not be located below the source region. Seismic waves from the Bonin earthquake were recorded by a number of broadband stations in a wide range of distance around the world. Along with the data collected by IRIS DMC, we examined broadband data of F-net in Japan. Since high-frequency waves, which could be associated with the descending Pacific slab, were observed in eastern Japan, we used the data only from western Japan, which range from 7 to 16 degrees in distance. Changing the depth of the 660-km discontinuity in iasp91, we obtained spatiotemporal distribution of slip on a finite fault by the multiple-time-window method (Kuge, 2003; Kuge et al., 2010). Relatively small amounts of slip were estimated above the assumed 660-km discontinuity. When the 660-km discontinuity was assumed below the earthquake source, the waveform fit became worse, compared with the cases above. These results are consistent with the observation of a simple pulse for P waves over western Japan from an aftershock.

*S01-3-04
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

The January 2017 Barrow Strait Earthquake and Subsequent Seismic Activity in Arctic Canada

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At 23:47 UT on 8 January 2017, a magnitude (MW) 5.9 earthquake, one of the largest in eastern Canada during the last 50 years, occurred just offshore of Somerset Island, in Barrow Strait 92 km from Resolute in northern Canada. The earthquake occurred near the Boothia Uplift of the Boothia-Ungava Seismic Zone and was well recorded by the newly refurbished seismograph in Resolute (RESN). An earthquake of this size is expected about once every 300 years based on the statistics for the Somerset-Cornwallis Island seismic source zone; the rate for Barrow Strait by itself is higher than for the larger region. The mainshock was followed by a rich and ongoing aftershock sequence. As of 6 February 2017 there were eight aftershocks of magnitude 3.0 or greater and numerous smaller ones with the largest being a magnitude 5.1 event that occurred at 17:55 UT on 9 January. Moment tensor inversion of the mainshock and largest aftershock indicates that they were predominantly thrust faulting events on a northwest-striking plane consistent with past events in Barrow Strait including the 1987 magnitude 5.2 event that occurred 30 km NW of the January 8 mainshock. We will discuss the characteristics of the mainshock, seismotectonics of the region, an analysis of the aftershock sequence, depth estimation using a variety of methods such as moment tensor inversion and analysis of teleseismic depth phases. On 20 January 2017 another moderately large (MW 4.7) earthquake occurred in the Arctic Islands about 97 km from Isachsen, Nunavut. This event has an oblique-thrust mechanism. There are few recorded aftershocks for this event but we note that the closest station is at a distance of 475 km. While too far (575 km) to be considered an aftershock of the Barrow Strait earthquake, the occurrence of the two events over a short time period raises the question of a causal relation.

*S01-3-05
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Long Duration of Ground Motion in the Paradigmatic Valley of Mexico

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Built-up on top of ancient lake deposits, Mexico City experiences some of the largest seismic site effects worldwide. Besides the extreme amplification of seismic waves, duration of intense ground motion from large subduction earthquakes exceeds three minutes in the lake-bed zone of the basin, where hundreds of buildings collapsed or were seriously damaged during the magnitude 8.0 Michoacan earthquake in 1985. Different mechanisms contribute to the long lasting motions, such as the regional dispersion and multiple-scattering of the incoming wavefield from the coast, more than 300 km away the city. By means of high performance computational modeling we show that, despite the highly dissipative basin deposits, seismic energy can propagate long distances in the deep structure of the valley, promoting also a large elongation of motion. Our simulations reveal that the seismic response of the basin is dominated by surface-waves overtones, and that this mechanism increases the duration of ground motion by more than 170% and 290% of the incoming wavefield duration at 0.5 and 0.3 Hz, respectively, which are two frequencies with the largest observed amplification. This conclusion contradicts what has been previously stated from observational and modeling investigations, where the basin itself has been discarded as a preponderant factor promoting long and devastating shaking in Mexico City. Supporting our theoretical findings, by means of an array beamforming analysis using data from several subduction earthquakes recorded at hard-rock sites next to the basin we show that most of the coda waves (i.e., between the 30% and 45% of the total seismic energy) in those sites correspond to backscattered energy radiated from the basin. (Work published in www.nature.com/scientificreports ; 2016; DOI: 10.1038/srep38807)

*S01-3-06
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S01. Open session

Difference in energy radiation from earthquakes with similar moment magnitude and focal mechanism: the broadband body-wave magnitudes of the 2014 Ludian and Jinggu, Yunnan Province, China, earthquake

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The August 3, 2014, Ludian, Yunnan Province, China, MS6.5/MW6.2 earthquake and the October 7, 2014, Jinggu, Yunnan Province, China, MS6.6/MW6.1 earthquake, although with similar moment/surface wave magnitude and similar near-vertical strike-slip focal mechanism, caused sharply different disasters. The former was with fatality/missing up to about 700 and injury about 3,000, and the latter with fatality 1 and injury about 300. To investigate the role of seismic radiated energy in causing such a difference, we analyzed 142 broadband (BB) vertical recordings of the Ludian earthquake and 138 BB vertical recordings of the Jinggu earthquake, with epicentral distance 6o to 80o. We calculated the broadband cumulative body-wave magnitude mBc. It is shown that the mBc of the Ludian earthquake is about 0.3 higher than the Jinggu earthquake. This indicates that, beyond other causes such as social vulnerability, secondary disasters such as landslides, and local effects caused by both the Doppler effect of the seismic source and the site response of the buildings, radiated energy contributes significantly to the difference of the earthquake disasters. The result suggests that in seismological observation and interpretation, routine measurement and fast report of mBc will play an important (and sometimes unique) role in the earthquake emergency response and the rescue and relief actions.

*S01-4-01
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Recent earthquakes at Disko Island, Greenland, with focal mechanisms

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During the first weeks of April, 2016, the little village of Qeqertarsuaq on the south coast of Disko Island, West Greenland, experienced a large number of earthquakes. A large (for the region) Mb 4.7 event was recorded internationally, preceded by six smaller events in the hours before the larger event. A massive aftershock series followed during the following weeks with more than 150 events, two of which were Mb 4.5. The majority of the earthquakes occurred within an area of 50 x 50 km just south of Disko Island. The location of the main event suggests a source depth in the upper crust. Sparse coverage of seismic profiles in the region show faults in the upper crust that have been active in recent geological time. Focal mechanisms for the larger earthquakes are compared with focal mechanisms for Baffin Bay between Greenland and Canada.
Earthquakes are not uncommon in the area. Since recording began in Greenland more than 100 years ago, nearly 700 earthquakes have been recorded in the nearby area. Since 2009 the station coverage in Greenland has increased from 5 stations to 19 today due the GLISN project (www.glisn.info). In this period two additional swarms of earthquakes have been recorded (23 events in August 2010 and 20 in February 2015), none of which had a large initial event. Prior to the GLISN project a similar sequence of 33 earthquakes was recorded by a temporary net of seismometers in February 2006, with magnitudes ranging from 1.2 to 3.5.

*S01-4-02
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

New insights into volcano-tectonic seismicity patterns in the Virunga Volcanic Province, Democratic Republic of the Congo, from a new broadband seismic network (KivuSNet)

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The Kivu Basin is located in the bordering region of the Democratic Republic of Congo and Rwanda, in the Western branch of the East African Rift. Here the active volcanoes Nyamulagira (the most active in Africa) and Nyiragongo (host to the largest persistent lava lake on Earth) threaten the city of Goma and neighbouring agglomerations. For many years already, urbanisation in that region undergoes sustained rapid growth, and the region counts 1 million inhabitants today. In 1977 and 2002, eruptions of Nyiragongo caused major disasters. Destructive earthquakes can also affect the region, as was the case in 2002 in Kalehe (Mw 6.2) along the western shore of Lake Kivu, or in 2008 in Bukavu (Mw 5.9), south of Lake Kivu. Until recently, modern seismic monitoring infrastructure was lacking in the area, leaving many aspects about the volcanic activity and seismicity up to speculations.
In the frame of several Belgo-Luxembourgish collaborative research projects (the most recent one being RESIST: “Remote Sensing and In Situ Tracking of geohazards", funded by the Belgian Science Policy and Luxembourg National Research Fund), we deployed the first dense real-time telemetered broadband seismic network in the region, with the first two stations in 2012 and 2013. It is now a network of 15 stations and still under continuous development. Many KivuSNet stations are co-located with GNSS KivuGNet stations, and three KivuSNet sites are in addition equipped with infrasound arrays.
We present an introduction to the key features of the network and first scientific results, including unprecedented insights into tectonic and volcanic seismicity patterns as well as the continuous tracking of tremor sources and implications for magma migration patterns of the past 2 ½ years. KivuSNet opens a new window for the state of knowledge on the seismic and volcanic activity in this highly threatened region and represents an indispensable tool for monitoring operations of the Goma Volcano Observatory.

*S01-4-03
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Monitoring eruption activity using temporal stress changes at Mount Ontake volcano

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On 27 September 2014, Mt. Ontake in Japan produced a phreatic (steam type) eruption with a Volcanic Explosivity Index value of 2 after being dormant for seven years. The local stress field around volcanoes is the superposition of the regional stress field and stress perturbations related to volcanic activity. Temporal stress changes over periods of weeks to months are generally attributed to volcanic processes. Here we demonstrate that quantitative evaluation of temporal stress changes beneath Mt. Ontake, Japan, using the misfit angles of focal mechanism solutions to the regional stress field, is effective for eruption monitoring. We estimated focal mechanism solutions of 316 VT earthquakes beneath Mt. Ontake from August 2014 to December 2016, assuming that the source was double-couple. Pre-eruption seismicity was dominated by normal faulting with east-west tension, whereas most post-eruption events were reverse faulting with east-west compression. The moving average of misfit angles indicates that during the precursory period the local stress field beneath Mt. Ontake was rotated by stress perturbations caused by the inflation of magmatic/hydrothermal fluids. Post-eruption events of reverse faulting acted to shrink the volcanic edifice after expulsion of volcanic ejecta, controlled by the regional stress field. The deviation of the local stress field can be an indicator of increases in volcanic activity. The proposed method may contribute to the mitigation of volcanic hazards. The time history of average misfit angles showed non-negligible enhancements in several periods after the 2014 eruption. These observations suggest that some re-pressurization/de-pressurization processes repeated after the 2014 eruption.

*S01-4-04
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Long-term monitoring of of seismic velocity around a source fault of the 1995 Kobe earthquake

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Temporal variation in seismic velocity structure around Nojimafault, which ruptured at the time of 1995 Kobe earthquake (Mw6.9), has been measured for 17 years from 2000 to 2017 using Accurately Controlled Routinely Operated Signal System (ACROSS). We constructed the ACROSS sources which generate horizontally polarized seismic wave on the southern end of Nojima fault and started the measurement in 1998. The generated seismic wave were detected by borehole-type seismometers deployed at the bottom of 800-m- and 1700-m-deep boreholes near the ACROSS sources. The temporal changes in travel time and amplitude of P-, S-, and later phases have been monitored.
As a result, gradual decreases in the travel times of the body waves as well as that of the later phases were detected. The decreasing rate decayed during the 22 years after the Kobe earthquake. This decay corresponds to the decay of permeability change measured by water injection test into the fault, which was repeated from 1997 to 2009. The velocity variation should be a result of crack healing around the fault after the earthquake.

*S01-4-05
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Exhaustive analysis of surface wave propagation in a combined use of active and passive surveys for detailed site characterization

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Determining the soil geophysical properties related to seismic amplification, at sites where ground motion is being recorded, is a key effort in engineering seismology. Besides explaining local seismic response, it improves the robustness of the estimation of seismic attenuation and of earthquake magnitude. For the purposes of site characterization, surface wave (SW) methods are nowadays regarded as an established technique.
We present site characterization surveys conducted at selected sites of the Swiss strong motion network SSMNet; active and passive SW data were jointly acquired. The novelty we introduce with respect to previous works is the technique we use to derive the parameters of SW propagation. We have developed and apply a maximum likelihood technique for the joint analysis of Love and Rayleigh waves. They are identified in the collected data and selected with a Bayesian information criterion; wave parameters are estimated modeling jointly all recorded components. As outcome, SW dispersion data, Rayleigh wave ellipticity and prograde/retrograde sense of particle motion are retrieved. Originally developed for passive data, we have also adapted this technique for active acquisitions, accounting for the propagation of circular wave fronts. This allows us, in the surveys we present, i) to merge information from active and passive measurements, covering shallow and large depths; ii) to use the same 2D array for active and passive acquisitions (simplifying survey logistics). Finally, limited to active data, we have included the modeling of Rayleigh wave intrinsic attenuation. This enables the reconstruction of the damping ratio profile of the subsoil, besides that of shear wave velocity. We show that the joint assessment of the characteristics of SW propagation (velocity, ellipticity, sense of particle motion, attenuation) improves the robustness of their estimation, and also the reliability and completeness of the obtained subsurface geophysical models.

*S01-4-06
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Investigation of deep sedimentary and crustal structures with passive seismic methods

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Passive ambient-vibration measurements are well established to investigate the uppermost shear-wave velocity structure, usually limited to few hundred meters depth. Tomographic methods based on earthquake recordings are widely used for the study of the deeper crust, at depths of the order of several kilometers. We plan to fill the gap between both depth ranges using passive array measurements. The study area is the Swiss foreland.
From a geological perspective, the Swiss foreland mainly consists of quaternary deposits on top of Molasse and Mesozoic deposits of variable thickness ranging from about 1 to 5 km above the crystalline basement. The goals of our measurements are the identification of the main impedance contrasts in the subsurface, their comparison with a-priori information and the computation of local shear-wave velocity profiles. In order to investigate different depth ranges, several array configurations of increasing size were deployed, ranging from small scale of about 10 m to very large scale up to 10 km of inter-station distance.
We will present the results of first array measurements in the Molasse basin in northern Switzerland. Three arrays of different size have been deployed. The recorded data were processed using different techniques. The H/V and ellipticity curves for all single stations were computed, while the array processing yielded Rayleigh and Love wave dispersion curves in a wide frequency range. We used different methods, including three-component high-resolution FK, SPAC and Wavefield Decomposition (WaveDec). The final step of the analysis is the joint inversion of all available data and the definition of shear-wave velocity profiles including their regional variations. We discuss the applicability and resolution power of seismic passive methods to the investigation of shallow and deep structures.

*S01-P-01
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Fast hypocenter determination with a 3D velocity model and its implication for seismicity monitoring

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Hypocenter location still has important role in any kinds of seismic analysis. Clear image of aftershock distribution helps us to understand the fault geometry of big earthquakes and tectonic meaning of the event. A precise velocity model is indispensable to get good image of hypocenter distribution. Velocity models have been estimated with seismic surveys and tomographic analyses of natural earthquakes. A crustal structure model of the Japanese model was obtained with the tomographic method (Katsumata, 2010), in which the Moho discontinuity depth distribution was estimated as well as the velocity distribution in the layers. The velocity model indicated various characteristics of the Japanese Islands, which reflected the history of the islands formation.

It usually takes a long time to estimate a hypocenter location with a 3D complex velocity structure. It sometimes takes more than one hour to locate a single hypocenter using a 3D velocity model because of the very time-consuming calculation in ray-tracing. The time had been reduced by introducing 3D travel time table for each station (Katsumata, 2015). Almost any events can be located within one seconds. It was confirmed that calculation time was reduced by about 1,800 times.

The effect of the inhomogeneous velocity structure on the event location is often observed in determination of shallow inland events. Events under a thick sediment layer tend to be located at the deeper with 1D velocity model than that with 3D model. Aftershock distribution of the 2004 Mid-Niigata Earthquake was one of such cases. Similar depth difference was recognized in the activity of the 2016 Kumamoto Earthquake. However, precision improvement in offshore areas seems to be limited. Noticeable improvement is sometimes seen, for example, events off Ibaraki Prefecture. It is considered that local velocity structure difference makes the difference in the effects for offshore event locations.

*S01-P-02
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Moment tensor inversion of shallow offshore earthquakes in the Nankai subduction zone using a three-dimensional velocity structure model

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On April 1, 2016, Mw 5.8 earthquake (2016 Southeast Off Mie earthquake) occurred near the epicenter of the 1944 Tonankai earthquake (e.g., Ando, 1975). To investigate seismic activity around the Tonankai area, source mechanism of the 2016 Off Mie earthquake should be required. Since seawater, accretionary prism (low-velocity sediments) and subducting Philippine Sea plate exist beneath the epicenter region, it is difficult to obtain accurate source mechanism via conventional one-dimensional analysis (Nakamura et al. 2015; Takemura et al. 2016). Thus, in this study, we conduct moment tensor (MT) inversion using Green's function via finite-difference method (FDM) simulations of seismic wave propagation in a three-dimensional (3D) heterogeneous velocity structure model.
The model of 3D simulation and technical details are same as in Takemura et al. (2016). The 3D heterogeneous velocity structure, including topography, sedimentary layer, crust and subducting Philippine Sea plate, is referred from the Japan Integrated Velocity Structure Model (JIVSM; Koketsu et al., 2012). By using displacement waveforms of NIED F-net for periods of 30-100 s, we estimate an MT solution of this earthquake. The result with minimum variance reduction is the optimal solution with source mechanism and centroid depth.
The optimal result is characterized by a low-angle dipping faulting at a depth of 11 km, where the upper surface of the Philippine Sea plate exists closely. Obtained result reproduced not only long-period (30-100 s) displacement waveforms but also polarity of short-period (< 2 s) P waves. Observed P-first arrivals at land stations show apparent velocity of approximately 7 km with up polarizations and are interpreted head wave propagating along oceanic Moho of the Philippine Sea Plate.

*S01-P-03
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Local Magnitude, ML Scale for the Philippines: Investigation of Hypocentral Distance Dependence

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We conducted a grid search for the local magnitude coefficients using broadband waveforms of local earthquakes recorded by the Philippine Seismic Network (PSN). We selected sets of the coefficients which explained the data relatively well without large hypocentral distance dependence. Compared to the distance correction functions of southern and central California and the central United States obtained from previous studies, the distance correction functions for the selected sets of the coefficients are similar to that of southern California.

To further investigate hypocentral distance dependence, we calculated the medians of local magnitude residuals for 10 bins ranging from 0 to 1000 km. When the distance correction function for southern California is used, there is a hypocentral distance dependence larger than 0.1 magnitude unit, although the scatter of the residuals is large. We show that it is possible to find local magnitude coefficients with smaller hypocentral distance dependence by a grid search.

Keywords: Local magnitude, distance correction, grid search

*S01-P-04
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The Mechanism of Rare Earthquakes in Pidie Jaya, Aceh Derived from Source Parameter and Shear Wave Splitting Tomography

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On December 7, 2016, a rare and unexpected earthquake with a moment magnitude (Mw) of 6.5 struck Pidie Jaya, Aceh. According to Indonesian Meteorological, Climatological, Geophysical Agency (BMKG), the earthquake was located in 5.19o N, 96.36o E, with a depth of 10 km. Approximately 11,000 houses and 104 dead casualties were reported. It was assumed that the earthquake relates to Samalanga Sipopok fault which is located in the northern part of Aceh and has a mechanism of strike-slip. In regard to this event, we deployed 9 seismometers for a month in this area to identify aftershocks. The objective was to confirm the geometry of fault plane and the earthquake mechanism. We recorded 330 aftershocks between December 14, 2016 and January 15, 2017. We manually picked P- and S- wave arrival times and applied probabilistic non-linear method to locate hypocenters. Furthermore, we calculated the moment magnitudes using Brune's model and processed several samples of focal mechanisms using full waveform inversion. It can be observed that the aftershocks are distributed in Southwest – Northeast direction from the mainshock. The magnitudes decreased along with time and the focal mechanism shows a strike-slip faulting. Moreover, we also analyzed anisotropy parameter using 3-D shear wave splitting (SWS) tomography to delineate the fault plane. The high degree of anisotropy and crack density were observed around the interpreted fault structure. The distribution of earthquakes and anisotropy may reveal an unprecedentedly unknown fault in the study region.

*S01-P-05
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S01. Open session

Rupture process of the 1979 Tumaco, Colombia, earthquake using teleseismic body waves

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We investigated the rupture process of the 1979 Tumaco earthquake using the teleseismic P-wave records at WWSSN stations with epicentral distances between 30 and 100 degrees. The records consist of six vertical and three horizontal seismograms. We used the fault geometry model of Yoshimoto and Kumagai [AGU fall meeting, 2016], which was constructed from slab model Slab 1.0 [Hayes et al., JGR, 2012]. We calculated Green's functions using the method of Kikuchi and Kanamori [BSSA, 1991] and applied the waveform inversion scheme of Kikuchi et al. [EPS, 2003] to determine the spatial and temporal slip distribution. Our analysis indicated Mw 8.3 and the total rupture duration of about 120 s. The rupture propagated northeast from the rupture initiation point with a rupture velocity of 2.0 km/s. The large slip area was estimated in the northeastern part of the source region with the maximum slip of 3.5 m. This large slip area is consistent with reported regions of large tsunami height and strong shaking intensity. White et al. [EPSL, 2003] estimated the average plate coupling ratio in the 1979 earthquake source region to be only 30 %. From this coupling ratio and the average slip of 2.4 m in our slip model, the recurrence interval of the 1979 earthquake was estimated to be 174 years. This suggests that the 1906 Ecuador-Colombia earthquake did not rupture the source region of the 1979 Tumaco earthquake. This interpretation is consistent with that proposed by Yoshimoto and Kumagai [2016].

*S01-P-06
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S01. Open session

Stress drop characteristics of the 2008-2016 Storfjorden earthquake sequence

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An earthquake sequence started in 2008 with a ML=6.0 earthquake in the Storfjorden area to the southeast of Spitsbergen that is part of the Svalbard archipelago. Since then, more than 2000 earthquakes have been detected by the regional seismic stations with about 30 of them being of moderate size. Most recently (2016) a double earthquake of magnitude ML=5.2 and ML=4.8, respectively, occurred to the northeast of the initial main cluster. While in this intraplate region the dominant compressive stresses were thought to originate from the Northern Mid-Atlantic ridge, the mechanisms found for the larger earthquakes range between strike-slip and normal solutions and indicate pull-apart tectonics due to north-south extension. While this presentation will give an updated overview of the complete sequence, the focus is on estimating static stress drop. For the larger earthquakes stress drop was measured from the source displacement spectra. However, for earthquakes below ML=4.0 we systematically searched for correlated events pairs that were about one magnitude apart. The smaller of the two events was then used as empirical Green's function and deconvolved from the larger event to obtain the source time function. This allowed to look for differences in stress drop between various clusters of correlated events. One of the significant findings was that the largest and initial earthquake had the highest stress drop comparable to other intraplate earthquakes. This result was verified by comparing the observed ground motion data to intraplate attenuation curves.

*S01-P-07
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S01. Open session

Adding manual picks from OBS stations into the ISC Bulletin: the example of the 7D Cascadia Initiative Community Experiment

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The International Seismological Centre (ISC) integrates instrumental seismological parametric data (e.g., hypocenters, phase arrival times, amplitudes/periods, moment tensor solutions etc.) from ~130 agencies around the world to produce the most comprehensive bulletin of the Earth's seismicity, the ISC Bulletin. Whilst the main contributors to the ISC are monitoring agencies operating at various scales, the ISC Bulletin can benefit from additional parametric data coming from temporary deployments. In this contribution we show how manual picks from the OBS data of the Cascadia Initiative Community Experiment (http://www.fdsn.org/networks/detail/7D_2011/, IRIS OBSIP, 2011) were integrated into the ISC Bulletin and used for the ISC hypocentre relocation. In total approximately 6400 picks of primary and secondary arrivals have been picked for large teleseismic earthquakes and moderate-to-large earthquakes in the local/regional distance range. Despite the high noise level of OBS waveforms over 50% of the picks contribute to ISC relocations. We encourage researchers processing data from temporary deployments to send parametric data to the ISC in order to improve the configutation network of the ISC locations; this in turn will improve specialised ISC datasets (e.g., ISC-EHB, GT and ISC-GEM) and offer an even denser dataset to ISC users (e.g., for tomographic studies).

References:
IRIS OBSIP (2011): Cascadia Initiative Community Experiment - OBS Component. International Federation of Digital Seismograph Networks. Other/Seismic Network. doi:10.7914/SN/7D_2011

*S01-P-08
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

The current status of the ISC Bulletin

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The International Seismological Centre (ISC) is a non-governmental, non-profit-making organization funded by 69 research and operational institutions in 45 countries around the world and several sponsors from the public and commercial sectors. The ISC's primary role is the production of the Bulletin – the definitive summary of global seismicity from 1904 till present, based on reports from over 130 seismic networks worldwide.

The historical part of the Bulletin (pre-1964) now contains seismic arrival times at stations from the International Seismological Summaries (ISS) and from individual station bulletins digitized as part of the ISC-GEM project. The modern part (post-1964) is currently being re-worked under the Bulletin Rebuild project: we re-compute ISC hypocentres using the ISC location algorithm and the ak135 velocity model, and re-assess ISC-reported magnitudes making them more robust and reliable. We also collect and integrate previously missing bulletins from permanent and temporary seismic networks, filling the gaps in time and space.

Hours to days after seismic event occurrence, the ISC Bulletin contains integrated preliminary reports from networks that are substituted with final reports within 12-24 months. After review by ISC analysts, preliminary data in the Bulletin are substituted with Reviewed, presently after ~36 months. With the introduction of the new Visual Bulletin Analysis System, the time required for analyst review is set to reduce.

ISC data are distributed via the ISC and several mirror websites, e.g., those at IRIS DMC, University of Tokyo, LLNL, China Earthquake Administration, CTBTO, and are available on a series of DVD-ROMs. We also issue the printed Summary of the ISC Bulletin that gives information on the ISC, procedures and data formats, analysis of incoming data and the data in the ISC Bulletin; as well as invited publications on notable seismic events and history, and the status of individual seismic networks and their procedures.

*S01-P-09
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Automatic classification and onset estimation of seismic P and S wave signals recorded at local seismic network using artificial neural networks

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Automatic detection and onset estimation of seismic P and S wave signals are essential in automatic seismic event location systems. The problem of phase classification is studied by utilizing multiple parameters of different types each computed in several frequency bands. P and S wave signals have fundamentally different polarization properties. The input parameters depending on signal polarization in this study included rectilinearity, principal ellipticity, global polarization parameter, eigenresultants, quadratic resultant and predicted coherency. Several statistical parameters were also used. They included skewness, kurtosis and Jarque-Bera test. Variance in time of several of the parameters were added to the input database. Different amplitude ratios were used also. Statistical parameters were computed separately from vertical and horizontal channels. All parameters were computed at 6 different frequency range and time window combinations resulting 210 input parameters. The parameters were computed from 10634 seismic traces of local events creating 2.2M new time-series. Independent training, testing and validation datasets selected from these time-series consisted ~1.5M inputs each. Artificial Neural Networks (ANN) are a robust and efficient tool in classification using large amount of input parameters. A deep ANN with 4 hidden layers was used for classification of the P and S wave signals. Final validation showed that 98% of signals were classified correctly. Magnitudes of the events are usually in range 1.5>ML>0.5 and event to station distance less than 200 km. Similar method was applied to automatic onset estimation. The data set was recorded in local seismic network on Botnian Bay coast, Finland. The network is collecting information of microearthquakes in an area around a planned nuclear power plant.

*S01-P-10
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S01. Open session

The use of seismic arrays in geodynamic monitoring of the East European platform

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The Institute of the Dynamics of Geospheres (IDG) of the Russian Academy of Sciences (RAS) operates several small-aperture seismic arrays, which are used in monitoring of the geodynamic regime of the East European platform (EEP) for a decade. One permanent array MHVAR (“Mikhnevo") and four portable arrays are equipped with 3-C seismometers improving their overall performance. Four from five arrays are installed on thick sediments that may negatively affect their sensitivity. Nevertheless, since its inception in 2004, MHVAR has been demonstrating all advantages of array processing. It reduces the amplitude detection threshold by a factor of 3 to 5 and respectively improves the seismological catalog issued by the Geophysical Survey (GS) of RAS for the EEP. In routine processing, beamforming enhances detection of P- and S-waves from near regional (ML>1.5) and teleseismic (mb>4.5) events. Within the EEP, mining blasts generate a bigger part of detected signals, and the method of waveform cross correlation (WCC) is optimal for detection and identification of repeating signals. The WCC is also suitable for the study of natural seismicity and related tectonic and geodynamic processes. For example, we used WCC to recover 12 aftershocks of the mb4.9 earthquake, which occurred on August 7, 2016 near the town of Mariupol. For this, we merged data from two IDG arrays and three primary stations (AKASG, BRTR, and KBZ) of the International Monitoring System. A similar station configuration was successfully used to detect and identify dozens of mines and quarries within the EEP. Overall, the combine use of seismic arrays and the WCC method enhances the effectiveness of artificial events identification, reduces the threshold of seismic catalogue completeness, and improves the accuracy of relative location and magnitude estimation most important for correct tectonic interpretation of natural seismicity.

*S01-P-11
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Development of JAMSTEC Ocean-bottom Seismology Database (J-SEIS) to download DONET Event Data and Borehole Continuous Data (4)

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Japan Agency for Marine-Earth Science and Technology (JAMSTEC) have developed a database of seismic data observed in the Nakao Trough in southwest Japan. We have operated JAMSTEC Ocean-bottom Seismology Database (J-SEIS)* for research and education since April 2016.
J-SEIS is download system of seismic waveform data, the downloadable data are continuous data of Long-Term Borehole Monitoring System (LTBMS) and event data of DONET (Dense Ocean-floor Network System for Earthquake and Tsunamis).
During IODP Exp. 332 in December 2010, the first LTBMS was installed into the borehole site (C0002:KMDB1) located 80 km off the Kii Peninsula, 1938 m water depth in the Nankai Trough. Furthermore, During IODP Exp. 365 in 2016, the second LTBMS was installed into the borehole site (C0010:KMDB2) located sea area off the Kii Peninsula. It consists of various sensors in the borehole such as a broadband seismometer, a tiltmeter, a strainmeter, geophones and accelerometer, thermometer array as well as pressure ports for pore-fluid pressure monitoring. The signal from sensors is transmitted to DONET in real time. J-SEIS allows users to download seismic waveform data as continuous data of SEED format.
Event data consists of strong motion (EH type) and broadband (BH type) seismograph data observed at DONET1, it is produced referring to event catalogues from USGS and JMA (Japan Meteorological Agency), Magnitude greater than 6 for far-filed and greater than 4 for local seismicity, respectively. This system allows users to download these seismic waveform data as event data of SEED format.
J-SEIS allows users to download continuous and event data on the graphical user Interface. Further, it is also possible to download directly seismic continuous data by specifying parameters (terms, channel, and station) of URL address (e.g. data download page like “Web Service" of IRIS).

* J-SEIS : JAMSTEC Ocean-bottom Seismology Database
URL https://join-web.jamstec.go.jp/join-portal/en/

*S01-P-12
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S01. Open session

Very wide observation range of the developed borehole stress meter and comparison with STS seismometer

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We have developed a stress meter which can record continuous stress variation in a deep underground. The Tohoku earthquake (M9.0) occurred on 11 March 2011 in Pacific Ocean. The stress meters operated by Tono Research Institute of Earthquake Science (TRIES) could beautifully record whole wave forms caused by the earthquake. The stress meters can respond from DC frequency. However, almost all of STS seismometers in Japan scaled out and could not record larger amplitudes of the wave forms. It is important to record long period seismograms for especially earthquakes happened in sea for estimating occurrence of large Tsunami. Therefore, we compared observation ranges among STS seismometer, stress meter and strain meter. We also investigated how large amplitude variations can be observed by stress meter and strain meter and characteristics of the meters. The main results obtained are as follows:

1. Vertical component of the stress meter of TOS borehole station (depth: 512m) recorded maximum amplitude of about 300kPa for the 2011 Tohoku earthquake. However, the stress meter can record amplitude of about 5 MPa for even high sensitivity setting up.

2. Stress meter and strain meter for even high sensitivity setting up have as 10 times wider observation range than that of STS seismometers.
.
3. The stress meter can observe not only stress but also strain. And observation range of strain meters are about 2x10^-4 , though maximum amplitudes of observed strain were about 5x10^-5.

4. The stress meter developed by us makes use of estimating Tsunami generation, determining magnitude and research of earthquake generation because it can record whole stress seismogram without scaling out even for gigantic earthquake.

*S01-P-13
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S01. Open session

High-frequency geophone with correction scheme for mine explosion monitoring

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The paper reviews correction method of frequency response of high frequency geophones: the method of multiplying the transfer sensor functions with the transfer function of correction filter of the 2nd order. This method broadens geophone's response function from 10 Hz to 0.8 Hz that was proved by shake table experiments: self-resonant frequency of the geophone with correction device was found as 0.8 Hz with sensitivity 19 V/(m/s) that corresponds to 3 dB.
In case of micro-seismic noise studying this scheme appeared proper to broaden lower edge of response function of geophone GS-20DX from 10 Hz to 2 Hz for signals of different amplitudes. If signal amplitude exceeds local noise level it's possible to register signals with the frequency down to 0.8 Hz (as shown in shake table experiments).
Correction scheme field tests were carried out on the base of mining bursts monitoring. We compared records of the short-period seismometer (0.5-40 Hz) and the geophone with correction scheme (0.8-40 Hz) that had been registered during summer 2016. Gained data are compliant.
Application of described scheme for low-aperture arrays can significantly decrease equipment cost for proper frequency range.
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*S01-P-14
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S01. Open session

RESIF Seismology Distributed System : Data and Services.

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RESIF (Reseau Sismologique et Geodesique Francais DOI:10.17616/R37Q06) is a nationwide French project aimed at building a high quality observation system to observe and understand the inner earth. RESIF seismic component deals with permanent and mobile seismic networks data, including dense/semi-dense arrays. Its goals are to create a
network throughout mainland France comprising 750 seismometers and geodetic measurement instruments, 250 of which will be mobile, and to distribute all seismic and geodetic data acquired by French reasearch institutions. RESIF seismology project is distributed among six different nodes providing real-time and qualified data and metadata to the
main data centre in Universite Grenoble Alpes, France. A web portal allows to explore and download seismic data and metadata. RESIF is fully integrated into the much wider European scale project EPOS. Data control and qualification is performed by each individual nodes. The poster will provide insights on the validation process of seismic data with two examples from volcanological and seismological observatories as well as dense networks from the mobile component of RESIF. We will also present tools developed to monitor stations, to collect
and to format metadata; currently used by operators of permanent broadband stations.
In addition, will then present data that has been recently made publicly available (mobile broadband networks in the
Alps the Pyrenees, and Antarctica). Data from RESIF is distributed through worldwide FDSN and European EIDA
standard protocols.

*S01-P-15
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S01. Open session

Data quality Improvement of the Algerian Digital Seismic Network (ADSN)

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The performance of a seismic network is linked with the quality and number of its stations. In Algeria, in order to implement a high quality network (ADSN), site selection and installation remain crucial taking into account many environmental aspects as security, radio link connections…etc.
From a database of seismic records collected from 2008 to 2016, an analysis year by year of the quality parameters of the several stations was carried out taking into account also the season's factor.
To monitor quality of the ADSN (Algerian Digital Seismic Network) stations, the noise level background is characterized for each station. The study includes seasonal and diurnal variations. Actually a web monitoring page help to control stations involved in the event location. A mobile application is also developed to different end users information relative of seismic events occurrence. In other hand, several technical works are made daily to test quality of the ADSN stations and to enhance the correct automatic event location. Among these tasks, state of health and rate of operation monitoring, seismometers and recorder calibration and sites selection for new broadband stations.
For nearby future, we plan to integrate existing stations and install new seismological stations for dams monitoring. Finally GIS (Geographic Information system) is set to manage the operation of our rapid warning system.

*S01-P-16
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S01. Open session

Design and Implementation of the National Seismic Monitoring Network in the Kingdom of Bhutan

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Bhutan-Himalayan district is located along the plate collision zone between Indian and Eurasian plates, which is one of the most seismically active region in the world. Recent earthquakes such as M7.8 Nepal earthquake in April 25, 2015 and M6.7 Imphal, India earthquake in January 3, 2016 are examples of felt earthquakes in Bhutan. However, there is no seismic monitoring system ever established in Bhutan, whose territory is in the center of the Bhutan-Himalayan region.

In this project, we are establishing the first national permanent seismic monitoring network in the Kingdom of Bhutan that is utilized for not only for seismic disaster mitigation of the country but also for studying the seismotectonics in the Bhutan-Himalayan region which is not yet precisely revealed due to the lack of observation data in the past.

We started establishing permanent seismic monitoring network of minimum requirements which is composed of six (6) observation stations in Bhutan with short period high sensitivity and strong motion seismometers as well as three (3) broad-band seismometers. Obtained data are transmitted to the central processing computers in the DGM (Department of Geology and Mines, Ministry of Economic Affairs) office in Thimphu. In this project, DGM will construct seismic vault with their own budget which is approved as the World Bank project, and Japan team assists the DGM for site survey of observation site, designing the observation vault, and designing the data telemetry system as well as providing instruments for the observation such as seismometers and digitizers.

We already started the operation of the five (5) stations out of six (6) located in Thimphu, the capital city, and other four (4) stations in Bumthang, Trashigang, Samtse, and Gelephu, and will soon start operation in Samdrup Jongkhar. We also deployed two offline seismic stations with short period seismometers in Gasa (Northern Bhutan) and Wangdu (Central) to assist permanent seismic network.

*S01-P-17
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S01. Open session

New steps towards local seismic hazard assessment of Bucharest (Romania)

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Bucharest, the capital of Romania, is affected by strong intermediate-depth earthquakes originating in the Vrancea seismic area. Bucharest is located in the the Moesian Platform, a large sedimentary basin (450 by 300 km) that reaches 20 km deep. Intensities up to VIII-IX have been reported in the city after four earthquakes with Mw>7 in the last century. The recorded ground motion is characterized by predominant long periods and has been interpreted as the combined effect of source mechanism and local geological conditions.
In order to better understand the effects of the geological structure beneath Bucharest, non-invasive geophysical techniques have been applied on seismic recordings (single-station and array) of both ambient vibrations and low-magnitude earthquakes. Using a 35 km diameter array of broadband seismometers, we analyzed the surface-wave field at very low frequencies (0.05 – 1 Hz). Estimates of Love and Rayleigh wave dispersion curves (fundamental and higher modes) and Rayleigh wave ellipticity were first retrieved and analyzed. In addition, the variation of the SH-wave fundamental frequency of resonance was mapped across the area. This information has been used together with the available borehole logs (<300 m) and geological interpretations of deep structures to characterize the shear-wave velocity structure down to 7 km of depth and to create a comprehensive 3D geophysical model of the basin underlying Bucharest.
Finally, we investigated the contributions of different seismic surface waves, such as those produced at the edges of the basin or by multipath interference (Airy phases of Love and Rayleigh waves), using the array processing technique MUSIQUE. We focused on frequencies between 0.1 and 1 Hz to better understand the complex nature of the H/V ratios in this range.
The results represent the starting point to simulate past strong events and will be further used to estimate the expected ground motion for different earthquake scenarios.

*S01-P-18
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Seismic Activity in the Central Tottori prefecture, Japan, with an M6.6 earthquake on October 21, 2016 analyzed by the Matched Filter Method

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Seismic activity in the central Tottori prefecture, southwest Japan was analyzed by using the Matched Filter Method (MFM). This swarm activity started with an M6.6 event on October 21, 2016. In this analysis, we implemented MFM as a pseudo-automatic hypocenter determination system that enables to locate earthquakes one by one. Our interest is if the MFM is a useful tool for immediate grasp of an ongoing intense swarm activity.

In the MFM analysis, selection of the template earthquakes is important since the spatial distance and magnitude difference among the template earthquakes affect the detectivity of earthquakes. For this purpose, we separately implemented the conventional event detection algorithm using STA/LTA to detect possible template earthquake in order to configure a set of template earthquakes. In the current analysis, we inspected the candidate earthquakes to select a new template whose spatial distance is greater than 2.5 km and magnitude difference is greater than 1.0 among existing templates. We repeated this procedure during 17 days from October 21 to November 7 to select a set of templates and finally selected 37 template earthquakes in this manner in the test period. When we obtained a new template, all the continuous record in the test period are scanned by the new template to detect new earthquakes.

During the test period of 17 days, about 7,000 earthquakes are detected and located with 37 templates. Comparison with manually inspected catalogue provided by JMA (Japan Meteorological Agency) indicates that the configuration of earthquake clusters well coincide with each other with slight differences and it was useful to understand the outline of the activity in the early stage. Although the manually inspected catalogue data is essential for the precise evaluation of a seismic activity, we suppose MFM is one of the powerful tools for an immediate grasp of the ongoing intense swarm activity.

*S01-P-19
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S01. Open session

The seismic sequence of the magnitude 5.7 crustal earthquake of 2014 of Focsani Basin (Romania) – relevant data regarding the stress field in front of the Southeastern Carpathians bend

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The seismic sequence of the crustal earthquake which occurred on November 22, 2014 in Focsani Basin is the strongest seismic energy release in front of the Southeastern Carpathians bend since 1900. The main shock with local magnitude 5.7 is the largest instrumentally recorded event in the region. Its aftershock sequence lasted about 70 days, more than 250 earthquakes with local magnitude > 0.1 were localized using the records collected by the Romanian seismic network.
The sequence occurred in the lower crust – the depth of the main shock was 40 km and the majority of the aftershocks had depths greater than 25 km – in the Focsani Basin (part of the Moesian Platform), nearby the contact point of three important tectonic units: the Scythian Platform, the Moesian Platform and the North Dobrogea Promontory. The epicenter distribution – along a NNE-SSW direction – follows the orientation of the Carpathian arc.
We present the detailed space-time evolution of the seismic energy release and determine the focal mechanism of the largest shocks, for which reliable P-wave polarity data are available – 11 events with local magnitude > 2.5.
The fault plane solution of the mainshock shows normal faulting with a dominant dip-slip component; the nodal planes are oriented SE-NW. Similar mechanisms are obtained for the strongest aftershocks – 2 events with local magnitudes above 4. Although a certain variability of the fault plane solutions of the weaker events is observed, the normal faulting dominates among the retrieved focal mechanisms.

*S01-P-20
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S01. Open session

Distribution of deep earthquakes in the subducting Pacific slab beneath Japan

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Generally, the number of earthquakes in slabs decreases with depth. However, the seismicity increases again in a depth range of 400–500 km. The mechanism of this phenomenon remains poorly understood, even though many hypotheses for the genesis of deep earthquakes have been proposed, which include dehydration-embrittlement hypothesis, transformational faulting, and shear instability. In this study, we analyzed 93 deep earthquakes (M⊠3.0) that occurred at depths of >300 km beneath Tokai area in Japan to understand factors that control the high seismic activity in the mantle transition zone.
First, we read P-wave polarities and determined focal mechanism solutions of earthquakes. Then, we picked arrival times of both P and S waves and relocated hypocenters by using double-difference earthquake relocation algorithm (Waldhauser and Ellsworth, 2000). The relocated hypocenters do not show a double-planed seismicity as is observed in Iidaka and Furukawa (1994). In the next step, we will relocate hypocenters with differential travel-time data derived from waveform cross correlations and constrain hypocenter locations with high accuracy. We will present detailed hypocenter distributions together with focal mechanism solutions, and discuss a plausible mechanism that facilitates deep earthquakes in the mantle transition zone.

*S01-P-21
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The McAdam, New Brunswick Earthquake Swarms of 2012 and 2015-16: Extremely Shallow, Natural Events

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Beginning in March 2012 people in McAdam, New Brunswick felt and/or heard many earthquakes within a 1x2 km area of the village. The largest events (MN < 2.6) were recorded by regional seismographs (closest was 65 km away). Public concern combined with the large number of events and their localization led the Geological Survey of Canada (GSC) to deploy 3 temporary instruments in McAdam. The University of New Brunswick provided a fourth. The instruments remained in place for several months and were then removed, as activity had largely died off by June 2012. There was a short resurgence late in 2015 with 7 felt events occurring 7-9 December. In February 2016, the swarm activity picked up considerably. In light of the increased activity, which included the largest earthquake of the sequence (MN 3.3 on 9 February 2016) the GSC redeployed 4 instruments which remained in place for several months until the activity again subsided. As of 1 November 2016, 164 earthquakes were located, some by enough stations to allow precise depth determination by one or more methods. All the earthquakes were extremely shallow, 0.0-1.2 km. The majority of epicenters lie in a WNW-ESE trending ellipse. Focal mechanisms determined for a small number of events are largely consistent with NE-SW compression and with regional earthquakes. Sixty-eight of the events were reported as felt, with several of the felt events being of magnitude less than 1.0. A strong motion recorder recorded a PGA of 9%g from an MN 1.7 earthquake at about 0.8 km hypocentral distance. There was no human activity that could have induced or triggered the swarm, and the cause remains unexplained. McAdam sits on Silurian metasediments intruded by the granitic Pokiok Batholith exposed just to the NW. No faults are mapped close to McAdam, but the events might have occurred on a NW-SE splay of the Fredericton Fault. Swarms like this are probably common in eastern Canada, but are seldom this well reported or recorded.

*S01-P-22
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Depth of earthquakes in Greenland

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Even though earthquake monitoring in Greenland has been carried out almost continuously for nearly 90 years, the depth of earthquakes occurring in Greenland are poorly known. For most of the monitoring period the seismic network in Greenland have included only four or less seismic stations, which is a very limiting factor in earthquake depth determination, especially taking the size of Greenland (more than 2 million km2) into account. Except for the few earthquakes that has been teleseismicly observed, depth determination based on the seismic network in Greenland, has been highly uncertain. However, with the initiation of the GLISN project (Greenland Ice Sheet Monitoring Network) (http://glisn.info/) in 2009, the number of seismic stations has increased, so that there today are 21 seismic stations in operation in Greenland all with realtime data connections. GLISN is mainly in operation for the observation of cryo-seismic phenomenas, but it provide a significant contribution to the recording of earthquakes. Here we will present our first results on the depth distribution of earthquakes in Greenland, our focus is mainly on the seven most active regions, identified along the coast areas, but depth of earthquakes occurring below the Greenland ice sheet are also presented.

*S01-P-23
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Mw 5.5 Gyeongju Earthquake of 12 September 2016 in Southeastern Korea: SCR Earthquake Sequence with Moderate Stress Drop

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On 12 September 2016 a Mw 5.5 earthquake occurred about 10 km South-Southwest of the ancient capital town of Gyeongju on the southeastern Korean peninsula. The mainshock was preceded by a Mw 5.0 foreshock by about 50 minutes and was followed by over 580 earthquakes with magnitude greater than 1.5 within the first 5 months. The 2016 Gyeongju earthquake is the largest instrumentally recorded earthquake on Korean peninsula. Accurate relocation of the earthquake sequence revealed that earthquakes are aligned along NNE – SSW trending, steeply dipping fault plane (dip=74º) with depth range from 13 to 17 km. Focal mechanism of the foreshock, mainshock and the largest aftershock, vertical strike-slip fault at depth, suggests that the event represents reactivation of buried high-angle faults in the Precambrian basement by the contemporary E–ENE trending regional horizontal compressive stress. Strike of the fault plane(s) of the 2016 Gyeongju earthquake sequence is consistent with the clearly developed NNE–SSW trending lineaments in southeastern Korea, which were formed at the end of Tertiary during an orogeny involving opening of East Sea of Korea (Japan Sea) to the east. The mainshock shows a static stress drop of ~10 MPa, which is somewhat lower than other similar earthquakes around the area. The Mw 4.6 Odaesan earthquake in 2007 that occurred about 200 km north of the Gyeongju sequence yielded a stress drop of 20 MPa. Low stress drops of a few MPa are reported for the earthquakes in the Yellow Sea region about 400 km west of the Gyeongju sequence. We compare stress drops of earthquakes in southern Korea with those of other SCR regions such as Virginia and Oklahoma, USA.

*S02-1-01
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S02. Anthropogenic seismicity

Insights into faults, crustal permeability, state of stress and earthquake physics from induced earthquakes in Oklahoma and southern Kansas

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A large region of north-central Oklahoma and southern Kansas in the central U. S. became seismically active starting in 2009. The earthquakes followed the initiation of high volume wastewater disposal by deep injection from newly developed unconventional oil fields and are understood to be primarily a consequence of disposal. These oil fields produce many times more water than oil, which is uneconomic to dispose of except by injection. To date, more than 700 deep disposal wells have injected one billion m3 of primarily co-produced water in to the highly permeable Arbuckle formation near the base of the sedimentary section. Owing to its high permeability (~1 Darcy), the pressure perturbation from individual wells merges into a low-pressure plume (< 1 MPa) spreading across a region that today covers more than 20,000 km2. This relatively small perturbation has activated hundreds of previously unknown basement faults in more than 1500 M >= 3 earthquakes, including the September 2016 Mw 5.8 Pawnee earthquake. These earthquakes characteristically occur on strike slip or normal faults that are near-optimally oriented for failure in the contemporary stress field. Seismicity on each fault characteristically initiates with small events before the occurrence of the largest in the sequence. Stress drops for the largest events average 10 MPa, releasing tectonic stress in what was previously an almost completely aseismic region. Consequently, parts of the crust where earthquakes occur must be near a state of failure equilibrium between the strength of the faults and the stress carried in the North American plate. In response to the seismicity crisis, regulators have mandated large reductions in fluid injection into the Arbuckle formation beginning in mid-2016. Seismicity rates are now falling in the region in response to this change; however, it may be years before the earthquake hazard returns to historic levels.

*S02-1-02
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S02. Anthropogenic seismicity

Trigger effects in the development of induced seismicity and the influence of human being over the natural seismicity of Kuzbass and Baikal regions of Russia

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The upgrowth of induced seismicity near excavations and trigger effects of anthropogenic factors impacting it was studied on the base of experimental data collected by temporary seismological networks placed near coal mines. Experiments were conducted near four coal mines in Kuzbass with different geotectonic conditions. These experiments proved the considerable contribution of powerful mining equipment vibrational loading to the anthropogenic seismicity process. In all cases while seismological networks were placed near excavations with powerful mining equipment, we observed seismic activizations accompanying the mining process. It would be sufficiently reasonable to state that high-production coal mining equipment works at the same time as a powerful vibrational source in subsurface and together with changes in fluid conditions could form pronounced induced seismicity near excavations. The appearance or disappearance of vibration exert influence on seismic conditions of activated area practically immediately. The qualitative assessment, based on the data of seismic events catalogue of Altay-Sayan region, of the influence of human activity on natural seismicity in designated areas is constructed. Local intervention in natural processes on examples of carrying out of industrial explosions at open-cast mining in Kuzbas and operation of a site of the railway along coast of lake Baikal is investigated. Gutenberg-Richter plots (GR-plots) are built for various samples of seismic events on time for Kuzbas region and variations of "b-value" are shown, which depends on time of observation (temporal). Also GR-plots are constructed for various strips along the railway near Baikal lake and the change in 'b-value" is discussed, which depends on offset from the railway (spatial). Finally the experiment with powerful vibration exciter is considered and the hypothesis of discharging effect of powerful influences on short distances is setting up.

*S02-1-03
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S02. Anthropogenic seismicity

Source parameters of the 2014 M5.5 Orkney earthquake sequence, South Africa, estimated by using near-field underground seismic arrays in gold mines

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The M5.5 Orkney earthquake occurred on August 5, 2014, near Orkney town, South Africa. The mainshock and aftershocks were recorded by underground arrays in gold mines, which are composed of 46 three-component geophones installed at 2-3 km depths. The sampling rate is 6 kHz. The observed waveforms display high signal-to-noise ratios and contain high frequency components up to at least 1 kHz, providing us an unprecedented opportunity for precise determination of aftershock distribution and source parameters. We determined hypocenters of 2000+ earthquakes from 4 August to 31 October 2014 by automatic earthquake location software from Home Seismometer Corp. (Horiuchi et al., 2011). Aftershocks distribute at a depth range of 4–7 km and form a 8 km-long near-vertical plane in the NNW-SSE direction. This distribution agrees with the mainshock focal mechanism (left lateral strike-slip faulting). We also determined 500+ aftershock focal mechanisms by using P-wave polarity data as well as body wave amplitudes, where almost all aftershocks could be explained by a double-couple solution. Stress tensor inversion reveals that strike-slip faulting with a NW-SE compression prevails throughout the region, which differs from the stress state on the mining levels (e.g., Ogasawara et al., 2012, 2013) but explains the occurrence of the mainshock. We also found that normal-faulting stress fields prevail around the southern part of the aftershock distribution, where low stress drop aftershocks are also prominent (Kazuki Sato BSc thesis, Ritsumei University). We infer that the mainshock terminated at the area where the stress field is different from the mainshock area and the stress level is low.

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*S02-1-04
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S02. Anthropogenic seismicity

State of the art in 3D reflection seismic interpretation: New insights into a complex structural architecture in the vicinity of Orkney M5.5 event, South Africa

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In August 2014, the M5.5 earthquake occurred in the Precambrian rocks of the Witwatersrand Basin, South Africa. The M5.5 mechanism was strike-slip faulting, which is different to a typical mine induced earthquake with normal-faulting. It is suggested that M5.5 was caused by dyke several hundreds of meters below the mining horizon. To better understand the structural complexity associated with the M5.5 and its aftershocks, we have processed and interpreted the high-resolution 3D reflection seismic data that were acquired in 2012 for gold exploration. A number of aftershocks fall within the 3D seismic volume providing unique opportunity to directly correlate structures mapped by seismics with the location of the aftershocks. It is envisioned that good seismic mapping of the shale units (4 - 7 km depths) and their associated structures would help to better understand the region's structural framework and to constrain the timing of activity of the faults.

The main outcome of the seismic interpretation has been an improved understanding of the complex structural architecture in the area. In particular, seismics has mapped normal (500 m maximum throw), north-northeast trending major faults and their subordinate structures. Faults are listric in form; dipping relatively steeply (65 - 70 deg.) at 1.5 - 2.5 km below the surface. At greater depths (4 - 5 km), below mining horizons, the dip decreases to about 40 to 50 deg. The seismic sections also exhibit the near-vertical features characterized by high amplitude attenuation associated with fault zones. These features crosscut, but do not displace, the entire stratigraphy of the basin. We interpret these near-vertical features as dykes with thickness from 1 m to 30 m, which may be possible sources of the M5.5 event.

It is, therefore, important to integrate the reflection seismic interpretation with the seismicity data so as to better understand the geometric nature of the structures associated with the M5.5 event.

*S02-1-05
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S02. Anthropogenic seismicity

Rupture Process of the 2014 Orkney Earthquake, South Africa

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An earthquake occurred at 10:22:33 UT on 5 August 2014 in the Klerksdorp district, the North West province of South Africa. This epicenter locates beneath Orkney town, which has 10 more than gold mines. The Council for Geoscience (CGS) in South Africa reported that the magnitude and depth was ML5.5 and 4.7 km, respectively. CGS have operated 17 seismic accleration observations on surface, and continuous acceleration seismograms were obtained at the time of the 2014 Orkney earthquake and following aftershocks. In this study, we analyzed the main shock rupture processof this earthquake, by using these accelation seismograms. First, we analyzed seismograms of mainshocks, found the initial rupture before main shock. That initial rupture has occured 0.3 sec before mainshock with a magnitude less than 4. By operating detailed aftershock distribution analysis, we found most of aftershocks occured surrounding mainshock and a seismic gap between aftershocks and goldmine blastings. Finally, to understand rupture process of the main shock, we surveyed for strong motion generating area (SMGA) by appling Isochrone backprojection method (IBM) to the mainshock's waveforms. SMGA distribution will fill the vacant space of the aftershocks distribution and main shock (initial rupture) hypocenter.

*S02-2-01
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S02. Anthropogenic seismicity

Reservoir-Triggered Seismicity in Brazil: characteristics and new cases

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We report here 26 cases of reservoir-triggered seismicity (RTS) in Brazil, emphasizing the cases observed in the last ten years. In worldwide terms Brazil presents a relatively high number of RTS. Nevertheless, if we consider the Brazilian high number of reservoirs with power to produce RTS this number is not so expressive. Not differently of the rest of the world, in Brazil the interest for the RTS subject began around the 70s when the first case had been identified (3.7 mb and V-VI(MM).
Studies on RTS in Brazil have been made there about 40 years ago, by the universities of Brasilia, Sao Paulo, Rio Grande do Norte and the Technological Research Institute of the State of Sao Paulo in partnership mainly with the national energy companies. In the middle of the 70´s initiated the reservoir seismographic monitoring and nowadays almost all the largest Brazilian reservoirs have seismic stations installed around them.
Two magnitudes 4 RTS earthquakes were observed, the biggest 4.2mb intensity (MM) VI-VII. About 80 percent of the RTS cases present initial seismicity, and the rest with delayed response with some cases having more than one main event. In Brazil, many cases of RTS exhibit a series of common characteristics. Furthermore, the magnitude of triggered event is not directly proportional to the depth of the water column or on the total volume of the reservoir, although, the triggered seismic activity has been more common in reservoirs with depth > 100 m (about a half of these reservoirs presented RTS). However, there are reservoirs that are higher than 100 meters that never had presented RTS and others with height less than 50 m with expressive triggered seismicity. Therefore, there is not a direct relationship between the maximum magnitude of a triggered earthquake and the dam height and the volume of the reservoir.
In this work, we will present the Brazilian RTS cases and discuss its features, highlighting the new cases, including that one´s not yet reported.

*S02-2-02
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S02. Anthropogenic seismicity

Hydrocarbon induced seismicity in Groningen, the Netherlands

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Since 2003 the dominant source of induced seismicity in the Netherlands is the Groningen gas field, one of the largest on-shore gas fields in the world. Due to the shallow source depth, at 3 km, even small magnitude events cause damage to buildings in the region. In 2012 the largest event, Ml 3.6, took place and more than 50000 damage claims were received by the mining company. Since 1995 a regional monitoring network is in operation, which has recently been extended over the Groningen field. Presently, more than 75 borehole strings with a maximum depth of 200 m and 90 surface accelerometers are operational. Since 2003 a new mining law is in place in the Netherlands, which requires for each gas field in production a seismic hazard and risk analysis. At the same time an increase in the activity rate was observed in the Groningen field, leading to the development of new hazard models and a re-assessment of parameters like the maximum magnitude. Understanding the earthquake process is essential in taking mitigation measures. Continued research is focused on reducing the uncertainties in the hazard and risk models. Key issues are the development of a site specific Ground Motion Model, improving the location accuracy of events, magnitude scaling and construction of a local shallow shear-wave velocity and Q model.

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Integrated Petrographic, Geomechanical and Seismological studies of rockmass behaviour during the final phase of ore extraction at Cooke 4 shaft in South Africa

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Seismic events, rockbursts and fault instabilities are prime concerns during the final phase of ore extraction at the deep (>1km) Cooke 4 shaft in the West Rand gold mining district, South Africa. This research aims to understand the seismic and mechanical behavior of the rockmass during the shaft pillar extraction operations by studying petrography, geomechanics and stress model, and to establish correlations with monitored microseismicity and underground mapping. The composition of the shaft pillar, observed through underground mapping and core sample analysis, was found to be quartzite, pebbly quartzite, argillaceous quartzite and conglomerate. Forming the roof of the hangingwall is the Ventersdorp Contact Reef (VCR) and Ventersdorp lavas, soft lavas. This affects the ore excavation operations and the stability of the pillar. Rock mechanical laboratory tests were restricted to rocks forming the shaft pillar, and the tests showed that quartzite has the strongest uniaxial compressive strength (UCS), followed by pebbly quartzite, argillaceous quartzite and lastly, meta-conglomerate, making quartzite the preferred rock type in pillars in terms of strength. Different lithologies exhibited specific mining-induced fracturing patterns in the hangingwall, mainly influenced by weak Ventersdorp lavas. Majority of microseismic events were found to be associated with the mining fronts. These seismic clusters delineated Ortlepp shears forming ahead of the stope owing to the excavation-induced stress field. This interpretation is supported by underground damage observations, stress model and ubiquitous discing in core samples. The acoustic emissions (AEs) were also concentrated in the vicinity of service excavations (tunnels). Some AE clusters were located away from excavations, likely delineating faults. In conclusion, microseismicity is largely influenced by structural discontinuities, ore extraction operations, and rock geomechanical properties in underground conditions.

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Very small repeating earthquakes on a geological fault at 1-km depth in a gold mine in South Africa

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We deployed an Acoustic Emission (AE) monitoring network consisting of 30 very sensitive AE sensors and 7 accelerometers at 1-km depth in the Cooke 4 gold mine in South Africa, where many earthquakes up to ˜M 3 were induced by stress buildup due to mining. Naoi et al. (2015) analyzed data obtained by the network during a 2 month period, and found very small repeating earthquakes of $-5.1 \leq M_w \leq -3.6$ which occurred in a region of ˜100-m extent on a geological fault. When applied to those repeater sequences, the Nadeau and Johnson (1998) empirical formula (NJ formula), which relates the amount of background creep and repeater activity and is well established for plate boundary faults, yielded an impossibly large estimate of the background creep. This implies that the repeaters were produced more efficiently, for a given amount of background creep, than predicted by the NJ formula.

In this study, we extended the analysis period to 14 months (from 7 April 2011 to 30 May 2012), and searched for repeaters among 3735 events that occurred on the fault, on the basis of waveform similarity and the proximity of their hypocenters relocated by the Double Difference method applied to relative travel-time accurately determined by cross correlation. Out of the 3735 events, 1572 events (42.1%) were identified as repeaters, which formed 360 groups. The largest group saw as many as 45 recurrences. Activities of some groups continued for the whole 14 months, whereas some groups exhibited a decrease in magnitude and disappeared eventually. We propose that the disappearance of the repeaters represents the dissipation of unstable patches of the fault, resulting from frictional wear of the contacts as fault creep progresses.

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Using empirical relationships to predict PPV for surface explosions

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Demolition sites have always been located in very remote areas, but with the ever increasing number of dwellings that are migrating towards these sites, monitoring of the ground vibrations has become a priority. This study monitored explosions from demolition ranges, by recording the ground motions generated, amount of explosive used and the distance from the source to each of the seismograph stations. The peak particle velocity (PPV) versus scaled distance (SD) values for each explosion and station were plotted and a multiple regression analysis utilized to obtain the equation parameters, or site constants for three predictor equations; the United States Bureau of Mines (USBM) equation, the Ambraseys-Hendron equation and the Langefors-Kihlstrom equation.
The data obtained is very scattered, but the higher coefficients of determination (R2) indicate that the site constants obtained using the USBM equation show better fits than for the other relations. In addition, the geological constants for many of the regions are similar for the USBM equation, thus it would seem that the USBM is the more reliable predictive equation to use for each of these sites. However, since most of the energy escapes into the atmosphere during blasting on the surface, one should caution against using the predictive equations designed for mining and excavation in the bedrock.

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Artificial Water Reservoir Triggered Earthquakes at Koyna, India

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Koyna, near the west coast of India is the most prominent site of artificial water reservoir triggered seismicity (RTS). Soon after the impoundment of the Koyna Dam in 1962, RTS was observed. It has continued till now. It includes the largest RTS earthquake M 6.3 on December 10, 1967; 22 M⊠5.0, and thousands of smaller earthquakes. The entire earthquake activity is limited to an area of about 30 km x 20 km, with most focal depths being within 6 km. There is no other earthquake source within 50 km of the Koyna Dam. An ICDP Workshop held in March 2011 found Koyna to be the most suitable site to investigate reservoir-triggered seismicity (RTS) through deep drilling. Studies carried out in the preparatory phase since 2011 include airborne magnetic and gravity-gradient surveys, MT surveys, drilling of 9 boreholes going to depths of ˜ 1500 m and logging, heat flow measurements, seismological investigations including the deployment of six borehole seismometers, and LiDAR. The Second ICDP Workshop held during 16-18 May 2014, reviewed the progress made and detailed planning of putting the borehole observatory was discussed. With improved location of earthquakes using the borehole seismic stations, the errors in hypocentral parameters have been brought down to ± 300m. The site of a 3 km deep pilot borehole was debated and among the 5 possible location, based on the seismic activity and logistics the location of the first Pilot Borehole has been finalized and the drilling has started.

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Scientific deep drilling investigations to probe reservoir triggered seismicity in the Koyna seismogenic zone, western India

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The Koyna region of western India is an outstanding natural laboratory to test hypotheses and model reservoir triggered seismicity through scientific deep drilling and monitoring in an intraplate tectonic setting. Persistent seismic activity during the past five decades including the M˜6.3 Koyna earthquake, 22 M ⊠ 5 earthquakes, 200 M ⊠ 4 earthquakes and a few thousands smaller earthquakes define a seismogenic zone covering an area of 20km x 30km. Most earthquakes are located in the depth range 2-7 km. The frequency of earthquakes in the region is modulated by the annual loading and unloading cycles of the Koyna and Warna reservoirs. A preparatory phase of investigations including drilling at 9 sites up to 1522 m depth has uncovered the Precambrian basement granitoids underlying the Deccan basalt in the region and shed new light on the subsurface geology and structure. Geological studies of basement granitoids are bringing out new lines of evidence to constrain the deformation mechanisms associated with recent and ongoing seismicity.

The Ministry of Earth Sciences, Government of India, has undertaken a two-phase scientific deep drilling and investigations plan. During the pilot phase, two boreholes up to 3000m depth are planned next to each other; one for making repeat measurements of geophysical, mechanical and hydrological parameters as well as multi-disciplinary laboratory studies on borehole samples, while the other would house a permanent array of seismometers and piezometers for long-term monitoring. Drilling of the first pilot borehole at a carefully chosen site is underway. The datasets acquired from this phase will be analysed together with the data from the existing network of 6 borehole seismometers (up to 1522 m depth) and 20 surface seismometers in the region, which will facilitate the design and set-up of a fault zone observatory at depth of ˜5000m during the next phase.

Crustal Configuration beneath Koyna-Warna Seismicity Region, Western India

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We present a 3D upper crustal configuration beneath Koyna-Warna region, western India, a site of continued seismicity over five decades in the continental interior. Seismic activities in the region are considered as a consequence of triggering of critically stressed regime due to artificial reservoirs. In order to delineate subsurface density and susceptibility models, Airborne Gravity Gradiometer and high-sensitivity Magnetic data (AGGM) are jointly inverted with constrained from several boreholes drilled through basalt exposed in this region. Model suggests an anomalous N-S oriented high density zone bound by low density rocks on either side in the north of Warna reservoir. Other prominent features are NW-SE oriented high and low density zones, south of Warna reservoir. The densities of sub-basalt rocks vary from 2650 to 2800 kg/m3. Interestingly, the majority of earthquakes are located at the contacts between rocks of contrasting densities.

Electrical image of Koyna-Warna seismic zone, India from large scale magnetotelluric studies

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A major scientific drilling program was launched by Ministry of Earth Sciences, Government of India with an intention to obtain an integrated model which can explain the genesis of reservoir triggered seismicity (RTS) at Koyna-Warna region, India. An exploratory phase covering a suit of geophysical investigations including magnetotelluric studies were carried out preceding to the deep drilling program. More than one hundred broad band magnetotelluric stations were recorded during 2012-14 field campaigns in the Koyna-Warna seismic zone. The apparent resistivity - phase pseudo section along Warna profile delineated a weak zone near Udgiri, coinciding drilling observations. Coast effect and the Dharwarian trend are apparently visible from the Phase tensor ellipses and the induction vector maps. A quick 2D modeling was carried out to the MT data along Koyna and Warna profiles using NLCG approach after rotating the impedances to TE and TM modes. Later, 3D inversion for all the impedance data using WSINV3DMT was carried out for the frequency range 0.01 to 1 s. Modeling results in conjunction with the tectonic of Koyna-Warna seismic zone is discussed.

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The seasonal variation regime of induced seismicity in the Koyna-Warna region, western India

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The five decade earthquake catalogue of the Koyna-Warna reservoirs region in western India was analyzed to study seasonal variations in seismic activity related to the annual cycle of loading and unloading of these reservoirs. Earthquakes started occurring in the region during early 1960s coinciding with the construction of the Koyna dam and subsequent filling of the reservoir in stages. The seismic activity continues till today. Our study reveals regularities in the seismic structure in time where the activity peaks thrice every year, viz., in autumn (September), in winter (November-December) and in spring (February-April). The monsoon season starts during June and ends in September every year. Seasonal seismic activity is the lowest in May and June when the water level in the reservoirs is minimum. The first peak in autumn is explained as the instant reaction of reservoir filling during monsoon season which saturates the system and adds an additional load due to the weight of the water in the reservoirs. The following two peaks in winter and spring follow the draining phase of the reservoir with a delay caused by the diffusion of water to deeper levels.
It is shown that intensities of both instant and delayed reaction to seasonal variations of water level change in time, their correlation also changes in time. The possible factors that may influence the intensity changes of seasonal components of induced seismicity are discussed.

Borehole seismological studies at Koyna-Warna: A unique example of the study of Reservoir Triggered Seismicity (RTS)

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The Koyna-Warna region located close to the west coast of India is an outstanding example of Reservoir Triggered Seismicity (RTS), where earthquakes have been occurring in a restricted area of 30x20 sq km since the impoundment of Koyna reservoir in 1962 and the Warna reservoir in late 1980's. So far the region experienced 22 earthquakes of M>5 including the largest triggered earthquake of M˜6.3 on Dec 10 1967, about 200 earthquakes of M˜4, and several thousand smaller earthquakes. The continued seismicity at shallow depths of 4-7 km in the Koyna-Warna region for the past 49 years was monitored through surface seismograph networks installed from time to time and the location accuracies were improved by enhancing the seismic network capabilities by various upgradations.
Recently under a deep drilling program initiated jointly by Ministry of Earth Sciences and CSIR-National Geophysical Research Institute to understand the earthquake mechanism at Koyna-Warna a very dense network of 22 surface broadband seismographs and six borehole seismographs up to depths of 1500m was installed forming a unique example to study the Reservior Triggered Seismicity (RTS) of Koyna-Warna. With the installation of this unique hybrid seismic network the detection capabilities and the accuracies of the hypo central parameters and the clear recording of the micro-seismic clusters have improved. There has been a significant improvement in the location of earthquakes and the absolute errors of location have come down to ± 300 m. All earthquakes of ML ⊠ 0.5 are now located, compared to ML ⊠1.0 earlier. The details of the seismic network along with the improvements will be presented here.
Key Words: RTS, Koyna-warna, Borehole Seismographs

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Seismotectonics of the Koyna region, India: based on focal mechanism solutions using borehole and surface seismological networks

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Artificial water reservoir triggered earthquakes have continued to occur at the Koyna region of western India since the impoundment of the Shivaji Sagar Lake in 1962. The seismicity is confined to a small region of about 30 km x 20 km. Recently, six borehole seismometers are deployed at depths varying from 981 m to 1522 m, surrounding the seismicity and well below the Deccan basalt cover to improve the accuracy of locations of these triggered earthquakes. Focal depths are estimated using waveform inversion approach and are mostly between 4 and 8 km in the Koyna-Warna region. Well constrained fault plane solutions are derived which provide vital information regarding the orientation of the fault planes. Analysis of the recent large earthquake of Mw 4.8 that occurred on 14 April 2012 has indicated a N30E oriented left-lateral strike-slip fault along the Donachiwada fault zone, where the largest M 6.3 Koyna earthquake of 10 December 1967 also occurred. For the first time, reliable fault plane solutions for about 50 smaller earthquakes of ML > 1.9 are estimated, that occurred since January 2015 using the sharp onsets on the high quality borehole seismic records which are complimented by a dense surface seismic network data. Our analysis presents a significant improvement in the estimation of absolute locations and fault plane solutions of earthquakes at Koyna.

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An overview of an ICDP project to drill into seismogenic zones of M2.0 – M5.5 earthquakes in deep South African gold mines (DSeis)

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The International Continental Scientific Drilling Program (ICDP) approved our proposal to drill into and around seismogenic zones where critically-stressed faults initiated ruptures at depth. The drilling targets include four ruptures equivalent to M2.0, 2.8, 3.5, and 5.5 earthquakes that dynamically and quasi-statically evolved in 2.9 Ga hard rock in the Witwatersrand basin, South Africa. A major advantage of our proposed project is the large quantity of high-quality data recorded by existing dense seismic arrays, both on surface and near-field underground, in three deep gold mines. Additionally, the great depths (1.0 to 3.3 km from surface) at which drilling starts reduces costs significantly and allows a larger number of holes to be drilled with the available budget. Flexibility in the drilling direction will also allow us to minimize damage to the borehole or the drilled cores. With ICDP funds, we will conduct full-core drilling of 16 holes at ranges of 50 to 750 m to recover both solid and fractured material in and around the seismogenic zones. This will be followed by core and borehole logging. Additional in-hole monitoring of rock deformation, ground motion, hydrology and geomicrobiology will be supported by co-mingled funds. We will also determine the 3D stress tensor near the collars of the holes using an overcoring technique that has been optimized for the highly-stressed ground and the working conditions found in deep South African mines. The measurement of the differential stress is based on the assumption that axi-symmetric variation in the diameter of the recovered core is caused by elastic expansion after drilling.

The M5.5 earthquake that took place near Orkney, South Africa on 5 August 2014 offers a special opportunity to compare models of the spatio-temporal evolution of both the main rupture and the aftershock activity determined by the inversion of ground motion measurements with direct observations.

Drilling will commence in early 2017.

Developing an Induced Seismic Mitigation Plan for the Proposed Utah Frontier Observatory for Research in Geothermal Energy (FORGE)

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The U.S. Department of Energy is proposing to develop a Frontier Observatory for Research in Geothermal Energy (FORGE). The goal for this facility is to develop and test new technologies and techniques related to enhanced geothermal systems (EGS). One of two potential locations for this facility (the Utah FORGE site) is the eastern Basin and Range in Utah's west Desert. The site is located directly west of Roosevelt Hot Springs and the operating Blundell geothermal power plant. One aspect of developing the FORGE facility is creating, in advance of any development, an induced seismic mitigation plan. In this paper, we present both completed and ongoing work related to the development of this plan. This work includes: reviewing the historical earthquake catalog; using the historical catalog to develop templates for subspace detection in order to lower the earthquake magnitude of completeness for the study area and to identify seismically active zones; reviewing previous seismic hazard analyses; the creation of deterministic ground-motion earthquake scenarios; risk analysis for the scenarios; and the analysis of newly collected seismic data. New seismic data includes data from a local five-station, broadband network, and data from a 96-element three-component Nodal seismic experiment that was operated for approximately one month. The new seismic data is being used for seismic detection and to develop initial seismic velocity images. Taken together this information will be used to develop a mitigation plan, such as a traffic light system, that can be used to modify production in order to minimize the risk from potential induced earthquakes.

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Mapping microseismicity induced by hydrofrac experiments in Europe

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Hydraulic fracturing can be performed to increase the rock permeability and enhance the exploitation of shale gas and has been increasingly applied in recent years on a global level, but remains poorly developed in Europe, partially because of the disputed environmental consequences. Here, we only consider the seismic hazard associated to hydraulic fracturing, and focus the problem from a seismological viewpoint. Although moderate magnitude events have been attributed to hydrofrac operations, the seismic response to fracturing is expected as local microseismicity. This poses important challenges to the detection and localization of weak events, identification of fracture migration and the spatial mapping of fracture distribution and permeability. At the same time, large data volumes currently recorded by dense microseismic networks provide unprecedented information on microseismicity. New tools need to be automatized so that large datasets can be handled and the data mined. Furthermore, a seismic detector needs to be quick, so that massive datasets can be processes in a reasonable time, whereas a seismic locator needs to be accurate, so that the small-scale patterns and migration of rupture processes can be resolved. We adopt here recently developed tools, designed to detect coincident arrivals of seismic energy at seismic stations in a local network and locate their source. We discuss two applications to hydraulic fracturing in Europe. The first is a small-scale experiment in a Swedish mine, where thousands of microfractures (acoustic emissions) are detected and located during an hydraulic fracturing experiment. The second concerns a recently exploited hydraulic fracturing site in Poland, monitored in the framework of the EU project SHEER. There, we analyse realistic synthetic data and real data to discuss one of the first cases in Europe, where an independent seismic monitoring of hydraulic fracturing operations was performed.

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IS-EPOS e- platform of EPOS Thematic Core Service ANTHROPOGENIC HAZARDS – a virtual laboratory for collaborative research experimentation

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Thematic Core Service ANTHROPOGENIC HAZARDS (TCS AH) provides virtual access to IS-EPOS e-platform, which integrates a wide-scale and high quality research infrastructure (RI) in the field of anthropogenic seismicity and other anthropogenic hazards induced by exploitation of geo-resources. The undertaking is developed in the framework of European Plate Observing System Program (https://tcs.ah-epos.eu/, infrastructural projects IS-EPOS, POIG.02.03.00-14-090/13-00 and EPOS IP, H2020-INFRADEV-1-2015-1). IS-EPOS platform of TCS AH is designed as e-research environment to ensure a researcher freedom for experimentation by providing a virtual laboratory with private workspace facility for processing streams. The integrated RI is used in novel ways with an access to (i) data gathered in the so-called "episodes", comprehensively describing a geophysical process, induced by human technological activity, which can become hazardous for people, infrastructure and the environment, (ii) problem-oriented services, with the particular attention devoted to methods analysing correlations between technology, geophysical response and resulting hazards, (iii) the intercommunity social functions: project brokering, common workspace of project shared by the project participants, upload/download data and codes to the common workspace. The platform serves research projects, e.g. "Shale gas exploration and exploitation induced risks, SHEER" project (Horizon 2020, LCE 16-2014). It allows to manage interdisciplinary data and data products from own personal or collaborative research as well as increases visibility of the project. In addition, platform provides expert knowledge and background information to the public sector and is also used as a teaching tool, e.g. within educational project ERIS-Exploitation of Research results In School practice, funded within ERASMUS+ Program of European Commission.

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Picking vs Waveform based detection and location methods for induced seismicity monitoring

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Microseismic monitoring is common operation in different georesources related industrial activities, such as oil&gas, mining or geothermal energy exploitation. In microseismic monitoring operations we generally deal with large datasets requiring robust automated analysis procedures. Such seismic datasets are often characterized by multiple events with short inter-event times or overlapping events; in this case, correct phase identification and event association are challenging, and errors can lead to missed detections and/or reduced location resolution. In the last years, to improve the performance of the current data analysis procedure various waveform-based methods for the detection and location of microseismicity have been proposed. These methods exploit the coherence of the waveforms recorded at different stations and do not require any automated picking procedure. Although this family of methods have been applied to different induced seismicity datasets, an extensive comparison with sophisticated pick-based detection and location methods is still lacking. We aim here to perform a systematic comparison in term of performance among waveform-based methods and the pick-based detection and location methods (SCAUTOLOC and SCANLOC) implemented within SeisComP3. SCANLOC is a new detection and location method specifically designed for seismic monitoring at local scale and is based on a cluster search algorithm to associate detections to one or many potential earthquake sources. On the other hand, SCAUTOLOC is a more “conventional" method and is the basic tool for seismic event detection and location in SeisComp3. This approach was specifically designed for regional and teleseismic applications, thus its performance with microseismic data might be limited. We analyze the performance of these methodologies for a synthetic dataset with realistic noise conditions and for induced seismicity data related to geothermal energy exploitation in St. Gallen (Switzerland).

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The Spatio-Temporal Variation of Seismicity in the South African Gold Mining Region

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The creation of a reliable earthquake catalogue with homogenous magnitude representation (Mw) is an essential step for the development of a probabilistic seismic hazard model. In preparing to conduct a seismic hazard of the Gauteng province in South Africa, such a catalogue of seismic events was compiled by combining publicly available earthquake information from the Council for Geoscience datasets. Two main datasets used in the creation of the catalogue are from the South African National Seismograph Network and the Gold Mines cluster networks. The SANSN catalogue consists of 49812 records of earthquakes occurring between May 1905 and December 2014, whilst the Cluster network catalogue has 7828 records between March 2010 and December 2014. Results of preliminary analysis of the data show a strong spatial and temporal variation in the occurrence of seismicity in the region. The seismicity characteristics of an area are usually described through the seismic hazard recurrence parameters, the mean seismic activity rate, λ , the Gutenberg-Richter b-value and the area-characteristic completeness magnitude, Mc. These parameters were investigated in terms of their temporal variation within the various mining regions of the Witwatersrand basin, using the ZMAP software package. The region was divided into four sub-regions, Klerksdorp-Orkney-Stilfontein-Hartbeesfontein (KOSH), West Rand, Central Rand and East Rand. In some regions mining stopped some years ago, yet seismicity continues to occur. Researchers linked this seismicity to flooding of the mines. Results of the analysis showed a strong influence of the temporal distribution of seismograph stations on the observed variation of recurrence parameters. However, physical processes such as the flooding of mines as well as the occurrence of large events also influenced the occurrence of events. A recommendation from this investigation was that time dependent seismic hazard assessment should be conducted for this region.

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Seismic hazard assessment for induced seismicity in the Middle Urals, Russia

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Traditionally common methods of seismic hazard assessment for wide territories including countries or large regions take into account only natural tectonic earthquakes. Such approach is obviously correct if the natural seismicity is dominant. But in some regions the contribution of induced earthquakes as well as nontectonic seismic events may be comparable to tectonic one or even prevail over it.
We have tried to estimate the contribution of induced earthquakes occurring in the Middle Urals that is the region of moderate seismic activity, where hundreds of deposits of different mineral types are under exploration. To obtain reliable result we followed the idea of probabilistic-deterministic forecasting of dangerous seismic processes according to common methodology offered by V.I. Ulomov. To estimate an actual seismic hazard for some mining districts, we used the data set of hundreds of natural and induced earthquakes and macroseismic data for the strongest ones. It was elaborated two prognostic models. The first one is the model of seismogenerating zones, describing parameters of whole variety of induced and man-made seismic sources that may occur in the region. The second one is the model of the seismic effect generated by induced earthquakes. Both models differ sufficiently from ones elaborated earlier only for natural seismicity by other researchers.
As result, a set of new maps in terms of seismic intensity and peak ground acceleration for the Middle Urals had been obtained. They show earthquakes only from three mine districts may generate the most significant seismic effect. In two districts there are conditions for generating shallow Mw 4.5 tectonic events, that caused by stress-strain changes due to deep mining. The third district may generate strong collapses. Hundreds of other zones are not able to induce events that produce effect greater than background normal level (5 points of MSK-64 scale).

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Identifying pathways for gas and fluid migration caused by fracking processes, with the use of criteria defined in equivalent dimension phase spaces

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SHale gas Exploration and Exploitation Risks (SHEER, www.sheerproject.eu) project aims at assessing short and long-term risks associated with groundwater contamination, air pollution and induced seismicity. The severity of each of these depends strongly on the unexpected enhanced permeability pattern, which may develop as an unwanted by-product of the fracking processes and may become pathway for gas and fluid migration towards underground water reservoirs or the surface. An important part of SHEER is devoted to monitor and understand how far this enhanced permeability pattern will develop both in space and time. Here we present a novel approach for identifying pathways for gas and fluid migration based on the transformation to equivalent dimensions. The transformation converts a set of any original parameters of seismic events in a set of their equivalent dimensions, which are strictly comparable. The latter set builds a phase space, whose metrics is Euclidean. These features of equivalent dimensions make it possible to introduce any complex, multidimensional criteria for selecting seismic events. We present results of the analysis of an injection induced seismicity data from The Geysers geothermal field, which is used in SHEER as a proxy of seismicity accompanying shale gas operations. In addition to occurrence time, location and magnitude these seismic events are parameterized by moment tensors and spectral parameters. This allows to define and apply criteria for possible linking of fractures into gas migration pathways in a prescribed direction, based on fracture fault planes orientations, on closeness of locations, on sources radii and on angles between the fault planes.
This work was supported within SHEER: "Shale Gas Exploration and Exploitation Induced Risks" project funded from Horizon 2020 – R&I Framework Programme, call H2020-LCE-2014-1 and within statutory activities No3841/E-41/S/2017 of Ministry of Science and Higher Education of Poland.

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Discrimination of induced seismicity component in the seismicity of Sakhalin offshore hydrocarbon fields

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Sakhalin Island offshore hydrocarbon fields (Russia) are located in the region of high natural seismic activity. That causes a concern on the possibility to trigger a catastrophic earthquake by the hydrocarbon field developments in this region. The concern is backed by probably triggering nature of the catastrophic Neftegorsk earthquake in 1995 (Mw=7.2). That is why a local seismic network was installed along the eastern shore of Northern Sakhalin in 2006 prior to active phase of the offshore hydrocarbon field developments. The results of analysis of the seismic activity registered by this seismic network are considered in comparison with the natural seismicity registered by the regional seismic network in 1950-1990. It was found that while there are no proved sings of the seismic activity increase due to oil and gas production in the controlled region, some changes in the seismic regime take place: b-value became a bit higher than it was before; the distribution of the time intervals between successive events became of the Weibull type with the form parameter less than 1; local maximums of the seismic activity spatial distribution became closer to the boundaries of the developed hydrocarbon fields; the correlation dimension calculated by Grasberger-Procaccia method became smaller. All these changes are typical for induced seismicity.

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The Results of the Local Seismic Monitoring in the Underground Baksan Neutrino Observatory

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Underground Baksan neutrino observatory is located on the territory of the North Caucasus, near Tyrnyauz city. It consists of two horizontal tunnels going deep into the mountains over a distance of 4 km. The depth from the surface is approximately 2 km at the most remote point of the tunnels. Two neutrino telescope, low-noise physical laboratories and ancillary equipment are installed in the underground excavations. Since the Caucasus region is characterized by high geodynamic activity, local seismic array was deployed in the galleries of observatory. The principal aim of the array is to provide data for the assessment and monitoring of seismic hazard in the observatory. The monitoring system is installed in the most remote and the deepest part of the tunnel. The array consists of 6 vertical and one 3-component sensor Sercel L4C and has the aperture of 150 m x 370 m.
The site of observations is characterized by extremely low levels of background seismic noise. The noise level almost coincides with NLNM (Peterson, 1993) in the frequency range of 0.1 - 5 Hz. It increases slightly at higher frequencies, but remains very low. Thanks to so favorable conditions, seismic sensors detect a large number of local and regional seismic events with hypocentral distances from few hundred meters to hundreds of km. Seismic events above magnitude ML=-2 are representatively registered within the distance of 10 km. Due to high sensitivity, the monitoring system daily registers from tens to a few hundreds of weak seismic events occurring in the neighborhood of the tunnels. These events occur mainly within the two local areas. One of them is located directly under the tunnels at a depth of 1.5 km, the second - at distance from 1.5 to 4 km to northeast from the monitoring system. Most of these events have a tectonic nature, but every month registers up to several tens of events that may be associated with the processes of the movement of fluids in the rock mass

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Experiment to Trigger a Moderate-sized Earthquke

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We are proposing an experiment to understand the initiation of large earthquakes by inducing seismic events on a shallow fault with water injection. Increasing the fluid pressure near an active fault will reduce normal pressure on a fault and bring it closer to failure, according to the classic Coulomb failure criterion. A study to monitor the water pressure and subsequent triggered earthquakes can help answer some fundamental questions in seismology about the stress levels that cause earthquakes and the physical conditions that are necessary for a large earthquake to occur.
Possible sites for such an experiment would be transform faults near mid-ocean ridges, such as the East Pacific Rise. Seismicity in these regions is quite shallow and accessible with ocean boreholes of 2 to 3 km depth. In such settings, moderate (M5 to M6) earthquakes occur at repeat intervals of 5 to 15 years. We would like to conduct a water injection experiment at one of these sites a few years before the expected earthquakes recurrence, to try to trigger an early occurrence of the event. Also, moderate earthquakes in these regions are usually accompanied by active foreshock sequences.
What is the water pressure needed to trigger an earthquake ? Assuming a recurrence time of about 15 years and a stress drop of about 2 MPa for an M5 earthquake, to trigger an earthquake 2 years early, we would need to increase the shear stress 0.3 MPa. Using the Coulomb failure criterion, this would correspond to a decrease of normal stress (or increase of pore pressure) of about 0.5 MPa. This increase is relatively small, however, the absolute pore pressure at 1 km depth is about 8 MPa. So pumping pressure of about 8.5 MPa would be necessary to reduce the normal stress on the fault. Such pumping pressures are possible using the current riser drilling technology.

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Possibilities of seismic monitoring in control of equipment and constructions of hydro-electric power plants condition

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Hydro-electric power plants of Russia situated in earthquake-prone regions are equipped with systems of seismometric and seismological investigations. The systems are integrated in one seismological grid which is maintained by GS RAS so that observations in local zones become more detailed and it let to investigate the seismicity in regions of hydrotechnical constructions location at a higher level. The investigations show that oscillations which source is working equipment of hydro-electric power plant, natural oscillations of dams, hydroacoustic self-oscillations in water conducts are found in microseisms records even at vast distances. We have developed methods of detection of these oscillations from records. With the usage of archived records for 15 years in a row we've analyzed the changes of natural oscillations of Sayano-Shushenskaya hydro-electric power plant dam – the biggest HPP in Russia. The Analysis of records from the seismological grid let us study out the processes happened during the accident at HPP on 17 august 2009 that helped to find out its reasons. Developed method according to continuous records of seismic stations lets us realize remote monitoring of vibratory condition of working hydroelectric units; monitor technical condition of dams through changing of natural oscillations of construction; get additional objective information which is necessary for investigation of reasons of emergency on hydro-electric power plants.

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Spatio-temporal variation in seismicity due to periodically alternating roles of reservoirs in the Koyna-Warna RTS zone, India

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Reservoir triggered seismicity (RTS) is well-accepted phenomenon describing the triggering of earthquakes through the local stress change due to the reservoir impoundment. Koyna–Warna region (KWR) in India is one such famous RTS site where earthquakes keep occurring after 50 and 30 years of Koyna(KR) and Warna reservoirs(WR) impoundment respectively and after the large M6.3 Koyna earthquake. Here we analysed the role of the reservoir water levels on spatio-temporal distribution of the earthquakes during 1968–2012. First, we analysed the seismicity data during January 2005-June 2012 recorded by seismic network operated by CSIR-NGRI. We performed a statistical analysis using Singular Spectrum Analysis(SSA) which shows that water level series has dominance of variance for annual periodicity. For the earthquake time series, a zone close to the WR, shows predominance of annual frequency, suggesting a compelling relation between seismicity and reservoir water level changes. To see an overall spatio-temporal effect of the reservoirs on the seismicity of the region, this type of study is required also for the earlier time period. In continuation of the previous work we divided the 1968-2004(MERI catalogue) earthquakes into different zones and performed same analysis. We found the effect of both the long-term and annual variations of the reservoir water level on the seismicity. Also an alternating role of the KR and WR on the seismicity, for the time period 1983-1995 the earthquakes near WR, during 1996-2004 the earthquakes near KR and during 2005-2012 again the earthquakes near WR, was found to be associated with annual variations in reservoir water levels. It appears that during the release of stress in region beneath one reservoir, the region beneath the other reservoir is accumulating stress and once the stress is released from one region other region is activated.

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3D Poroelastic Modelling of Reservoir Triggered Seismicity (RTS) in Koyna Region, Western India

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Reservoir triggered seismicity (RTS) is a well known phenomenon and about 120 sites have been identified worldwide where earthquakes have been triggered by filling of artificial water reservoirs. The Koyna region near the west coast of India is one of the globally recognised sites of RTS, where earthquakes have been occurring in a small area of 20 x 30 km2 since the impoundment of Koyna reservoir in 1962. Till date 22 earthquakes of M>5 have been occured in this region including largest triggered earthquake of M6.3 on 10 December 1967. RTS can be interpreted as a result of stress and pore pressure changes due to poroelastic response in the rock matrix. Although numerous studies have been carried out to constrain the mechanism of triggered earthquakes, a satisfactory model for this region remains elusive. Based on poroelastic theory we have used 3D finite element model (FEM) to simulate the development of stress and pore pressure due to reservoir impoundment. First we develop poroealstic model to investigate the effect of reservoir impoundment on local seismicity of the region. Preliminary studies suggest that impoundment of Koyna reservoir altered the pore pressure in the region and formed pore pressure front that propagated up to seismogenic depth through the crust with fluid diffusion. The change in stress regime of the region by the seasonal fluctuation in water level of the reservoir is found to be associated with the ongoing seismicity. However, measurements of different properties (Bulk modulus, Young's modulus, Poission's ratio, porosity, permeability etc.) through the ongoing deep drilling programme in Koyna region would provide a more realistic model of RTS.

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Rock strength variations in an active seismogenic zone: evidences from scientific drilling in Koyna, western India

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Reservoir triggered earthquakes have been occurring in the Koyna region of western India since the impoundment of the Shivaji Sagar reservoir in 1962. The earthquakes are located in the granitic basement rocks underlying a thick pile of Deccan flood basalt covering the region. Triaxial measurements on cores of granitic rocks recovered from recent scientific drilling provide unique opportunity to characterize the effect of ongoing seismic activities on rock strength properties. Nine cored boreholes have been drilled up to a depth of 1522 m in the vicinity of the Koyna seismogenic zone. The boreholes penetrated the total thickness of Deccan flood basalt and passed through a few hundred meters in the underlying granitoids. Laboratory data include measurements on granite gneiss, granite, migmatitic gneiss and mylonitised granite gneiss obtained from four boreholes. Salient results are as follows (i) Increase of rock strength with increasing confining pressure allow determination of the linearized failure envelopes from which the cohesive strength and angle of internal friction are calculated. (ii) Variable differential stress at different depths are the manifestations of deformation partitioning in close association of fault zone(s) or localised fracture zones. (iii) Fractures controlled by naturally developed weak planes such as cleavage and fabric directly affect the rock strength properties, but the majority of failure planes developed during triaxial tests is not consistent with the orientations of pre-existing weak planes. The failure planes may, therefore, represent other planes of weakness induced by ongoing seismic activity. (iv) Stress-strain curves confirm that axial deformation is controlled by the varying intensity of pre-existing shear in the granitoids. (v) Frequent occurrences of low magnitude earthquakes may be attributed to low and variable rock strength of the granitoids, which, in turn, is modified by successive seismic events.

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Deformations in rocks in the Koyna seismogenic zone, western India obtained through scientific deep drilling

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The Koyna region, located in the Deccan Flood Basalt Province of western peninsular India has been experiencing reservoir triggered seismicity since the impoundment of the Shivajisagar water reservoir in 1962. The 1967 M6.3 Koyna earthquake, 22 earthquakes of M greater than equal to 5, more than 200 earthquakes of M greater than equal to 4 and several thousand smaller earthquakes have occurred in the depth range 2-10 km and over a restricted area of approximately 20km x 30km. Scientific drilling carried out recently up to a depth of 1522 m in the vicinity of the seismogenic zone exposed the cratonic granitoids underlying the Deccan flood basalt and provided a unique opportunity to study the deformation features in an area of active seismicity. The salient results are as follows. (1) The basement rocks are dominantly composed of granite, granite-gneiss and migmatitic gneiss, typical of the Dharwar craton of peninsular India. (2) The intensity of shear fabric in the basement rocks indicate the presence of a highly strained shear zone. (3) The granitoids have been affected by later brittle deformation. (4) Occurrences of faults and fractures associated with fault breccias, fault gouge and pseudotachylite veins injected along tensile fractures are the direct evidences of seismic activity. (5) Prominent slickenlines with slickensides on fault surface, granular flow of crushed material within fault zone and intensive shattering of rocks observed without abundant alteration are related with the recent seismic activity. (6) Fracture density varies within and away from the fault zone which are frequently filled up with ferruginous secondary precipitation, signifying water channelization at depth.

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Geological and velocity structures of the Orkney M5.5 fault, South Africa

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In August 2014, the largest seismic event (M5.5) in a South African gold mining district took place near Orkney. It has been a question whether the M5.5 event was natural or mineinduced, and what geological structure was re-activated to cause the event.
It is also known that this earthquake occurred below the mining horizons in anarea characterized by complexgeological structures. However due to no economic interests at these depths, very little geological information is known. To better understand the structural complexity of the area, we have interpred the 2D and 3D reflection seismic data, which were acquired for gold exploration. The 2D/3D reflection seismic data are characterized by strong seismic reflectors, for example, at a dolomite-lava boundary, a lava-quartzite boundary, and quartzite-shale boundary. On the mining horizons from 2 to 3 km depth, the data show high optimum mapping of major fault zones, which correlate well with structures mapped underground. Interestingly, there is less disturbance at the depth of the M5.5 rupture (at least 5 km long horizontally and 3 km wide in the dip direction). It is suggested that a dyke hosted the M5.5 event. The near vertical dyke has been identified by underground mapping, however it is not visible on the seismic data probably due to its thickness being below the seismic detection limit.
It is also very important to calibrate the velocity field below the mining horizons in order to have more accurate absolute locations of targets of scientific interest of the M5.5 fault. To achieve this, we will convert our 3D seismic volume from two-way-travel times to depth using the stacking velocities obtained from the data processing. Subsequently, we will constrain our P-wave seismic velocity calibration using the stacking velocities and exploration borehole data. Following the calibration, the geological structure will be compared with the aftershocks and the mainshock fault slip distribution.

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Searching significant displacement zones of a M5.5 earthquake fault by forward and inversion analyses of strainmeter data at depth at a very close distance

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The largest event recorded in a South African gold mining region, a M5.5 earthquake, took place near Orkney, South Africa on 5 August 2014. It is an unusually well-recorded events: e the main- and after-shocks were recorded by 46 geophones and 3 Ishii borehole strain meters at 2 - 3 km depths with epicentral distances, delta < several km, and 17 surface strong motion meters with delta < 20 km. The upper edge of the planar aftershock activity dipping almost vertically was only some hundred meters below the sites where the strainmeters were installed. As the M5.5 seismic rupture is located within a distance that is drillable from the deep gold mine workings, ICDP approved a project to drill into the seismogenic zones. Moyer et al. (2016 SCEC) inverted the surface strong motion data, suggesting that there was significant fault slip, even at the mining horizon. However, no seismic rupture was mapped in the mine workings. So, the three strainmeters can constrain the configuration of the seismic rupture. As the population of the aftershocks varies significantly in space, we will discuss the relationship the fault slip and the aftershocks.
These strainmeters were only about 150 m o apart. However, their strain changes had different polarities while the other M4 strain changes with a similar hypocentral distance was the same. So, this information can place critical constraints on the location and configuration of the M5.5 fault.
First, we conducted a forward analysis by assuming a point source with the mechanism same as macroscopic one of the M5.5 faultingat a distance of a few km. However, no difference in the polarity of strain change was seen, suggesting that the effect of a finite size of the source with an edge much nearer than the point source had to be taken into account. We are attempting to invert the slip distribution on a source with a finite size together with surface strong motion data. We will report on the results at the meeting.

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An integrated estimation of the stress field in seismogenic zones in South African gold mines

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Although it is very important to know the details of the stress state in seismogenic zones for both seismology and safety in deep South African gold mines, it has not been feasible due to technical difficulties.
The Diametrical Core Deformation Analysis (DCDA) technique, proposed by T. Ito and A. Funato, uses an easy-to-make laboratory measurement of the diameters of drilled core, to estimate the differential stress on a plane normal to the borehole axis, which is calculated assuming that variations in core diameter are caused by axi-symmetric elastic expansion during drilling. We carried out DCDA for a total of 90 cores drilled from eighteen boreholes at three seismogenic zones in three deep-level South African gold mines in order to evaluate the reliability of the DCDA method and to clarify technical problems. Our measured cores included those from a high-stress-concentration area at 1.0 km depth in a shaft pillar where quasi-static growth of ruptures was elucidated by the SATREPS's acoustic emission observation, and from a M3.5 fault area at 3.3 km depth. We also conducted DCDA with cores that were recovered from over-coring stress measurements, and compared these results. It was observed that drilling quality sometimes affects DCDA results, as South African geological drilling crews don't care about the smoothness of the core surface because the main purpose of geological exploration drilling is to identify the lithology. However, if we scrutinize cores that are straight and smooth enough for DCDA, the DCDA results were in coherence with the results of the overcoring stress measurements. If we instruct drilling companies to use a stabilizer to straighten the drilling operation, we will be able to obtain more cores suitable for DCDA to elucidate stress variations along a borehole. We are currently developing a procedure to effectively select reliable DCDA results. At IAG-IASPEI 2017, we are going to make a follow-up report.

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Experimental measurements of seismic velocities on core samples and their dependence on mineralogy and stress, Witwatersrand Basin (South Africa)

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The measurement of seismic velocities, especially at great depths (~2 km-3 km) under high stress conditions (~65 MPa-70 MPa), are crucial for proper interpretation of reflection seismic data, and therefore, for understanding the seismic reflective nature of lithological boundaries. The integration of geological and geophysical concepts has enabled us to better understand the nature of the seismic reflectivity of the world's deepest gold-bearing reef, the Carbon Leader Reef (CLR). This was done by measuring the ultrasonic velocities and bulk densities as well as conducting mineralogical analyses on drill-core samples. The results show that the quartzite samples overlying and underlying the CLR exhibit similar velocities (~ 5028 m/s-5480 m/s and ~ 4777 m/s-5211 m/s, respectively) and bulk densities (~ 2.68 g/cm3 and 2.66 g/cm3). This is due to similar mineralogy and chemical compositions observed within the units. However, the CLR has slightly higher velocity (~ 5070 m/s-5468 m/s) and bulk density (~ 2.78 g/cm3) than the surrounding quartzite units probably due to higher pyrite content in the reef. In the data set it is found that seismic velocities increase with (1) decreasing silica content, (2) increasing iron and pyrite content and (3) decreasing grain size. Reflection coefficients calculated using the seismic velocities and densities at the boundaries between the CLR and its hangingwall and footwall units range between ~0.02 and 0.05, which is below the suggested minimum of 0.06 required to produce a strong reflection between two lithological units. This suggests that reflection seismic methods might not be able to directly image the CLR as a prominent reflector, as observed from the seismic data.Samples were also subjected to stresses of up to 65 MPa to investigate the dependence of ultrasonic velocities on stresses. Velocities increase with progressive loading, but at different rates in shale and quartzite rocks as a result of the presence of micro-defects.

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Estimate of the stress state in a close proximity to an earthquake source in a South African deep gold mine

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An earthquake of Mw2.2 (mainshock, hereafter) occurred at 3.3km depth in Mponeng mine, a deep gold mine in South Africa. A rupture plane of the mainshock diagonally cut a 30-m-thick gabbroic dyke. Yabe et al. (2013) drilled a borehole passing a source fault of the mainshock ~1.5 years afterward. They constrained possible ranges of stress magnitudes and the principal directions based on criteria of borehole breakout (BB) and core discing (CD) and a slip direction of the mainshock. In this study, we estimate the stress state in a close proximity to the source fault more tightly than Yabe et al. (2013) by using DCDA and DRA, in addition to information taken into account in Yabe et al. (2013). Considering that the mainshock occurred in the dyke, we divided the study are into three; host rock (quartzite), footwall dyke and hanging-wall dyke. The principal directions of stress in the host rock and the hanging-wall dyke were normal faulting one, being consistent with the CMT solution of the mainshock. But, the principal direction in the footwall dyke, where no borehole breakout or core discing was observed is reverse faulting one. To improve the estimation in the footwall dyke, we will measure stress magnitudes by DRA and compare with 3D model simulation.

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Evaluation of the induced risks caused by shale gas exploration and exploitation

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Shale gas operations may affect the quality of air, water and landscapes; furthermore, it can induce seismic activity, with the possible impacts on the surrounding infrastructure. SHEER (SHale gas Exploration and Exploitation induced Risks) project aims at setting up a probabilistic methodology to assess and mitigate the short and the long term environmental risks connected to the exploration and exploitation of shale gas. A test site located in Poland has been monitored before, during and after the fracking operations with the aim of assessing environmental risks connected with groundwater contamination, air pollution and earthquakes induced by fracking and injection of waste water. The severity of each of these hazards depends strongly on the unexpected enhanced permeability pattern, which may develop as an unwanted by-product of the fracking processes. The considered hazards may be partially inter-related as they all depend on this enhanced permeability pattern. Therefore they are being approached from a multi-hazard, multi parameter perspective. Methodologies have been developed to model fracture evolution around shale gas exploitation sites and a robust statistically based, multi-parameter methodology to assess environmental impacts and risks across the operational lifecycle of shale gas has been defined. All the developed methodologies are applied and tested on a comprehensive database consisting of seismicity, changes of the quality of ground-waters and air, ground deformations, and operational data collected from the ongoing monitoring episode (Wysin, Poland) and past episodes. Best practices to be applied in Europe to monitor and minimize any environmental impacts will be worked out with the involvement of governmental decisional bodies, private industries and experts
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*S02-P-11
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Induced seismicity in the region of the geothermal power plant at Insheim (central Upper Rhine Graben, SW Germany)

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The Upper Rhine Graben is the region with the highest temperature gradient in Germany. Since 2012 at Insheim a geothermal power plant is running in the central Upper Rhine Graben. It is accompanied by small to moderate induced seismicity. Before starting regular operation, hydraulic stimulation in April 2010 caused two seismic events of ML 2.2 and 2.4, which were felt by inhabitants. As a consequence the local seismic monitoring network of the company was improved by an additional scientific network within the research-projects MAGS and MAGS2. The densified seismic network of up to 14 surface stations is operated by the Federal Institute for Geosciences and Natural Resources BGR. The network was completed over time by 4 borehole stations, operated by the Local Seismological Survey of Rhineland Palatine LER and industrial partner. The event detection was done by a real-time cross correlation detector, which was developed as a SeisComP3-plugin. The network extension of less than 20 km made a standard determination of the local magnitude impossible. Therefore a relative magnitude was determined from the amplitude of master and detected events. The local 1D-velocity model was improved using VELEST. Corresponding station corrections are in accordance to the tectonic situation in the graben structure. Since the commissioning of the power plant in October 2012 about 810 events were identified and analyzed. As the area is densely populated the seismic background noise varies strongly resulting in a magnitude of completeness of 0.0 during the day and -0.4 during nighttimes. No seismicity is observed when the power plant is offline during maintenance periods. After recommissioning seismic activity is temporarily increased followed by a continuous decrease to a low activity level. Seismicity is located within the crystalline basement, which underlies the sedimentary graben fill. Focal mechanisms show the same major strike-direction as the local tectonic situation.

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Analysis of static stress transfer in the 2013 Valencia Gulf (NE Spain) seismic sequence

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The role of static stress transfer as an earthquake triggering mechanism is evaluated in the seismic sequence that took place in Spain's Valencia Gulf during September and October 2013. Earthquakes occurred in spatiotemporal correlation with injection activities conducted at the Castor Underground Gas Storage.

Coulomb Stress Changes (CSC) are quantified using the Coulomb Failure Function, which considers positive values as those promoting failure on the objective fault plane. Focal Mechanism (FM) solutions for the 8 strongest events in the sequence (M_L 3.5 - 4.3) are computed from full waveform inversion, and are then used to place the earthquake sources. A geometrical model containing both the FM-derived faults and the previously mapped structures in the area is built; CSC are then quantified along the sequence on all those faults.

We first assess whether the earthquakes can be explained based on static stress transfer on its own, and which of the previously mapped structures in the area is most likely to have slipped. The shortening on the Main Fault's characteristic earthquake cycle as a result of the experienced seismicity is also evaluated.

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Spectral Characteristics of the 2006 Quarry Blasts in the Tehran Region based on the TDMMO Network

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Tehran, the capital city of Iran, is located between the Alborz and Central Iranian tectonic zones. The Tehran region has several active mines in the south and southeast of Tehran. They produce quarry blasts with small magnitudes. In this research, spectral characteristics were computed for data from the Tehran Disaster Mitigation and Management Organization (TDMMO) network in the Tehran region. Data catalog was selected from previous studies from discrimination between microearthquakes and quarry blasts in 2012 by adaptive neuro-fuzzy inference systems method. Data was selected and analyzed for one year duration from Jan to Dec 2006. A total of 42 events quarry blasts data was extracted from the quarry blast catalog. The Brune's model is used to estimate source parameters like corner frequency and fmax. We obtained spectral characteristics for stations with a criterion for the signal to noise ratio; where signal to noise ratio was larger than 2. Magnitude (Mw) for the quarry blasts was calculated from 1.1 to 2.4 at epicentral distances between 8.81 and 43.90 km. Mean of moment magnitude for all signals and stations from 42 events has been evaluated to be Mw=1.6, and also mean of seismic moment obtained; M0 =4.4E+11 Nm. Maximum and minimum seismic moment for events are calculated to be 3.80E+12 and 5.10E+10 Nm, respectively. Other parameters like mean of corner frequency and fmax for this research for all signals obtained 1.7 and 4.8 Hz, respectively. Moreover, the average stress drop by the quarry blasts in the Tehran region obtained about 2.4 MPa. Comparison between the previous studies for a crustal earthquake in the Tehran region in 2009 and this study showed that stress drop for quarry blasts (2.4 MPa) are a bit smaller than the crustal earthquake (3.3 MPa). Results for this research can be used for both seismological and engineering purposes.

Analysis of ambient seismic noise levels for the SATREPS stations and their technical aspects

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The joint research project between Japan and Mexico entitled "Evaluacion del peligro asociado a grandes terremotos y tsunamis en las costas del Pacifico mexicano para la mitigacion de desastres" under the "Science and Technology Research Partnership for Sustainable Development" (SATREPS) program, contemplates the installation of 7 broadband seismological stations in the state of Guerrero, Mex. It is important to know the levels of environmental seismic noise, so in this work we present the seismic and background noise curves and compare the maximum admissible noise (HNM) and minimum (LNM) curves defined by Peterson (1993) to evaluate characteristics and design of the site of the seismic station, in addition to showing the technical aspects of the installation.

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The features of deep seismic structure of the area of junction of the Eurasian, Okhotsk and North American plates in Eastern Russia

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We compared the results of seismological studies and DSS with the known geodynamic reconstructions in the area of junction of the Eurasian, Okhotsk and North American plates. Comprehensive analysis of the materials of DSS and seismology represents a significant manifestation of this area of triple junction of the plates in the deep structures of the Earth's crust and in the Moho. Abnormal of seismicity and deep structure of the zone in the alignment of the profile of the DSS is a few hundred kilometers. In the seismic section it is marked by thin (37–42 km) crust (compared with the depths to the boundary M (57 km) in the adjacent northwestern area), low boundary velocities along the Moho (7.85 to 8.0 km/s), and low average (effective) velocities of P waves in the Earth's crust (˜6.3 km/s). In the plate junction area, the waves refracted from the Moho are weakly expressed in the wavefields. In the deep seismotomographic profile, this zone is marked by an extremely inhomogeneous medium crust and less contrasting reflections in the lower crust and Moho section (from the CDP data). In the wide plate junction area we have established low ratios of the velocities of P and S waves in the Earth's crust (⊠1.6–1.7) and low Poisson's ratio (⊠0.20), which might indicate a strong fragmentation of the crust. Position the main border between the Eurasian and Okhotsk plates specified, it passes approximately along the 144 meridian. This is confirmed by most of seismological and DSS data: the maximum number of earthquakes, maximum total released energy, major earthquakes, minimum depth of the hypocenters, local rise of the Moho and intracrustal boundary, lowest P-wave velocities in the crust, and low velocities along the boundary M. A joint border of Okhotsk and the North American plates that run along the fault Ulakhan is also contrasting on the seismic structure.

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A physical seismic modeling study of multi-azimuth seismic refraction for a horizontal transverse isotropic medium

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In order to investigate the characteristics of anisotropic strata, a multi-azimuth seismic refraction technique is proposed in this study. To simplify the problem, a two-layer (isotropy-horizontal transverse isotropy (HTI)) model is considered. A new travel time equation of the refracted P-wave propagation in the isotropy-HTI medium is derived, which is the function of the phase and group velocities of the HTI medium. The head wave velocity measured in the physical model experiment is the group velocity. The isotropic intercept time equation of a refraction wave can be directly used to estimate the thickness of the top (isotropic) layer of an isotropy-HTI medium, because the contrast between the phase and group velocities of the HTI medium is seldom greater than 10 percent in the earth. In addition, under an assumption, the contrast between the phase and group velocities of an anisotropic medium is small, the approximated travel time equation of a refraction wave is obtained. This equation is only dependent on the group velocity of the HTI medium. The elastic constants A11, A13 and A33 and the Thomsen anisotropic parameter (Epsilon) of the HTI medium can be estimated using the multi-azimuth seismic refraction technique.

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Envelopes of scalar plane wavelets propagating through 2-D random media with power-law spectra

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The envelope broadening and the peak delay of the high-frequency S wavelets from regional earthquakes are caused by scattering due to random velocity inhomogeneities in the earth. Several stochastic models have been proposed so far to describe these phenomena, such as the radiative transfer theory, the diffusion approximation, and the Markov approximation. Recently, Sato (2016, Geophys. J. Int.) proposed a new stochastic model to synthesize the envelope of a scalar wavelet radiated from a point source in a 3-D von Karman-type random medium having a power-law spectrum. The point is to split the spectrum into two components using the center wavenumber of the wavelet; the long-scale component produces the envelope broadening and the peak delay by multiple forward scattering, and the short-scale component causes amplitude attenuation by wide-angle scattering. The former and latter phenomena are evaluated by the Markov and Born approximations, respectively. Later, Sato and Fehler (2016, Geophys. J. Int.) extended Sato's theory into the case of a wavelet from a point source in a 2-D random medium. They showed that the synthetic envelopes, except for coda, match well the results of finite difference (FD) simulations. Emoto and Sato (2016a, Abstr. JpGU Meet.; 2016b, Abstr. Seism. Soc. Jpn. Fall Meet.) performed 3-D FD simulations and obtained the results consistent to the theory. In this study, we conducted FD simulations of scalar plane wavelets propagating through 2-D von Karman-type random media. We followed Sato and Fehler (2016) concerning the choice of the model parameters. We produced 15 media with different random seeds, and set 7 receivers at each propagation distance in every medium. The simulated seismograms were squared and stacked to obtain FD envelopes. We found they totally agree well with the present theory of a plane-wavelet version, except for the small von Karman order and the low center wavenumber of the wavelets.

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Statistical characteristics of scattered waves in random media based on 3D finite difference simulations

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Short-period seismograms show complex waveforms due to the scattering by the small-scale heterogeneities widely distributed in the solid Earth. The scattering causes the broadening of seismogram envelope, the attenuation of the peak amplitude with travel distance increasing, and the excitation of long lasting coda waves. In this study, we conduct the 3D finite difference (FD) simulation of the scalar wavelet propagation in the random heterogeneous media by using the Earth Simulator, a vector supercomputer managed by JAMSTEC. We analyze the characteristics of the scattered waves and compare them with the direct envelope synthesis methods, such as the radiative transfer equation with the Born approximation and the improved Markov approximation based on the parabolic approximation (Sato, 2016).
We confirmed that Born envelopes adequately fit with FD envelopes in the whole lapse time range, but improved Markov envelopes fail to model even at the peak of the envelopes for the case of a short correlation distance. On the other hand, improved Markov envelopes well model FD envelopes around the peak for the case of a large correlation distance. In this case, although the Born envelopes can't model the peaks of FD envelopes, late coda part of the envelopes are well reproduced. We also investigate the distribution of the squared amplitudes of FD traces. We find that the distribution varies as lapse time increases from the log normal distribution at onset to the exponential distribution at the coda. For the case of a short correlation distance, squared amplitudes obey the exponential distribution soon after the onset. This means that the random scattered waves are dominant from the early lapse time, since wide angle scattered waves are dominant. According to the FK analysis of the FD traces, squared amplitudes obey the exponential distribution before the energy fluxes of the scatted waves become isotropic.

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Propagation of a Scalar Wavelet through von Karman-type Random Media

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Short-period seismograms of small earthquakes show envelope broadening of an S-wavelet with travel distance increasing and excitation of long lasting coda waves. Their durations are much larger than the source duration. We may interpret the collapse of a seismic wavelet as result of scattering by earth medium heterogeneities. As a mathematical model, we study the propagation of a scalar wavelet through von Karman-type random media. When the center wavenumber of the wavelet is lower than the corner wavenumber, the radiative transfer equation with the Born approximation is useful for the synthesis of wavelet intensity. When the center wavenumber is in the power-law spectral range higher than the corner wavenumber, the Markov approximation method based on the parabolic approximation is useful for the synthesis of wavelet intensity; however, this approximation fails to synthesize coda excitation. In this case, we propose the following method for the synthesis of intensity time trace from the onset through the peak until coda for an impulsive radiation from a point source. Taking the center wavenumber of the wavelet as a reference, we divide the random medium spectrum into high– and low-wavenumber spectral components. Applying the Born approximation to the high–wavenumber component, we calculate the scattering coefficient, which is used in the radiative transfer equation for the calculation of intensity. Applying the Markov approximation to the low–wavenumber component, we calculate the envelope broadening and wandering factors. Convolution of these factors with the intensity calculated in the previous step leads to the Green function in the random media. By comparing the synthesized intensity time traces with FD simulations, we have confirmed the usefulness of the proposed synthesis from the onset through the peak until early coda.

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Role of localized heterogeneities on distortion of the apparent radiation patters: aftershock sequence of the 2016 Kumamoto earthquake

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The azimuthal variations of observed maximum amplitudes during local earthquakes (called the “apparent radiation patterns") are gradually distorted from the expected four-lobe patterns of a double-couple point source with increasing frequency and distance (e.g., Liu and Helmberger, 1985; Takemura et al., 2009, 2016). In this study, we examine the frequency- and distance-dependent characteristics of the apparent radiation patterns for P and S waves using NIED Hi-net waveforms of 30 aftershocks of the 2016 Mw 7.1 Kumamoto earthquake. Analyzed aftershocks are concentrated around two regions: the fault zone of the 2016 Kumamoto earthquake and Aso volcano area. Thus, we separately analyze the aftershocks in the fault zone (region A) and the volcanic area (region B). To quantify distortion from the four-lobe pattern, we calculate cross-correlation coefficients (CCCs) between observed and theoretical apparent radiation patterns as a function of normalized hypocentral distance kL, where k is wavenumber and L is hypocentral distance. Focal mechanisms are referred from the NIED F-net moment tensor catalog.
In the Chugoku region, CCCs show linear decay from 0.75 to 0.25 with increasing log(kL) from 1.64 to 2.85 and no significant difference of decay rate between P and S waves (Takemura et al., 2016). However, CCCs in this study show different characteristics from ones in Chugoku region. In region A, CCCs for P and S waves linearly decay in the same log(kL) range, but values are smaller (0.45-0.2) than Chugoku region, indicating that crustal heterogeneity in region A is stronger than Chugoku region. On the other hand, in region B, CCCs for S wave are very small (=0.15-0.2) even for small log(kL), but ones for P wave well agrees with Chugoku region, suggesting that around the volcanic area S-wave velocity structure has relatively strong heterogeneous nature compared to P-wave one.

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Modeling waveform anomaly across central Japan with scattered seismic waves as inferred from high-frequency simulations

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We model significant waveform attenuation anomaly observed in central Japan for intermediate to deep-focus (>190 km) earthquakes in subduting Pacific (PAC) plate. Analyses of Hi-net waveform data from the moderate sized (M 4-6) PAC plate events show differences in amplitude and duration of the high-frequency coda of P- and S-waves and their frequency content between the events occurring on northern and southern ends of the PAC plate. The northern events experience abnormally high attenuation of high-frequency (>1 Hz) seismic waves giving rise to spindle-shaped seismograms with strong converted phases and extended coda with very slow decay at the eastern stations. We investigate the cause of such waveform anomaly using the finite difference method (FDM) simulation of wave propagation through the subduction zone. Results of simulation carried out for a suite of plate models with key subduction zone elements show that the waveform anomaly is primarily explained by strong attenuation and defocusing of seismic waves by the localized highly heterogeneous low-wave speed anomaly, representing partial melting of the upper mantle. The data are secondarily explained by partial melting of the Philippine Sea (PHS) plate, mainly the hydrated basaltic oceanic crust, causing strong scattering of high-frequency seismic waves. The findings of this study have wide geodynamic implications such as the magma genesis and mechanism of intermediate earthquakes in young (<25 Ma) and warm subduction zones of central Japan.

Elastic vs. Acoustic Radiative Transfer Theory - Estimation of Seismic Attenuation Parameters in Germany

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In a first step a local data set is used to compare the outcomes of elastic and acoustic radiative transfer theory simulations. Frequency-dependent scattering and intrinsic attenuation parameters are estimated for the crustal structure beneath the W-Bohemia/Vogtland swarm earthquake region close to the border of Czech Republic and Germany using the two different modeling approaches. The parameter estimations are based on fitting synthetic envelopes to observed seismogram envelopes from shallow local events. The two different methods yield a very similar S-wave scattering and intrinsic attenuation model for the crustal structure in the Vogtland region with intrinsic attenuation being the dominant source of seismic attenuation. The similarity of the results indicates that for a simple half space setup, isotropic scattering and only modeling S-wave propagation, the acoustic approach suffices to obtain basic parameters about the attenuation properties of the medium. This is especially attractive, as analytic solutions to this approach exist, which can be computed efficiently and deliver results with only minor computational costs.
In a second step over 20 years of earthquake data from the German Central Seismological Observatory data archive is used to estimate the spatial dependent distribution of seismic intrinsic and scattering attenuation of S-waves for frequencies between 0.5 and 20 Hz in Germany using acoustic radiative transfer theory. We present preliminary results of the spatial distribution of intrinsic attenuation represented by the absorption path length, as well as of scattering attenuation in terms of the mean free path and compare the outcomes to results from previous studies. Furthermore catalog magnitudes are compared to moment magnitudes estimated during the inversion process.

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Trans-dimensional imaging of scattering and intrinsic Q structures

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Precise imaging of scattering and intrinsic Q structures is essential to describe wave propagation processes of high frequency seismic waves (>1Hz). The multiple lapse time window analysis (MLTWA) has been used to estimate these Q values by assuming constant Q in a study area (e.g., Hoshiba 1993). This study generalizes this MLTWA for a stable estimation of 2-D Q structures under the Bayesian framework in dimension variable space. Study area is partitioned into small areas by means of the Voronoi tessellation. Scattering and intrinsic Q in each small area are constant. We define a misfit function for spatiotemporal variations of wave energy as with the original MLTWA, and maximize the posterior probability with changing not only Q values but the number and spatial layout of the Voronoi cells. This maximization is conducted by using the reversible jump Markov chain Monte Carlo (rjMCMC) (Green 1995) since the dimension of posterior probability is variable. After a convergence to the maximum posterior, we estimate Q structures from the ensemble averages of MCMC samples around the maximum posterior probability. Synthetic tests showed stable reconstructions of input structures with reasonable error distributions. We applied this method for seismic waveform data of ocean bottom seismograms at the outer-rise area off Tohoku, and estimated Q values at 4-8Hz, 8-16Hz and 16-32Hz. Intrinsic Q are spatially uniform at all frequency bands, and scattering Q shows two distinct strong scattering regions at petit spot area and high seismicity area. These strong scattering are probably related to magma inclusions and fractured structure, respectively. While our generalization of MLTWA is still based on a classical waveform modeling in constant Q medium, this method can be a fundamental basis for tomographic imaging of Q structures in the crust.

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Scattering and attenuation structures beneath volcanoes inferred from envelope widths of volcano-seismic events

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It has been known that volcanoes exhibit highly heterogeneous structures with strong attenuation. Investigating scattering and attenuation structures is important to understand magma and hydrothermal systems beneath active volcanoes. In previous studies, the transport mean free paths (lm) and quality factors (Q) at volcanoes have been estimated by using seismic waveform data acquired by seismic experiments using artificial explosions, in which envelope waveforms (Wegler, JVGR, 2003) and spatio-temporal seismic energy distributions (Yamamoto and Sato, JGR, 2010) were analyzed. In this study, we propose a new approach using envelope widths of volcano-seismic events. The envelope width (p) is defined by the ratio of the cumulative amplitude (I) to the peak amplitude (A) of an envelope waveform of a volcano-seismic event in a 5-10 Hz band at each station. We used the analytical equation of Paasschens (Phys. Rev. E, 1997) for the radiative transfer theory in 3D isotropic scattering medium to derive the relationship of p with lm and Q. The estimated relationship indicated that p increases with decreasing lm and Q at a constant source-station distance, and p also increases with the source-station distance. We estimated p values for volcano-tectonic events at Taal volcano, Philippines, and at Nevado del Ruiz volcano, Colombia. Our estimated p values ranged up to 5 s and increased with increasing source-station distance. Our estimated relations between p and source distances at both the volcanoes were not explained by uniform lm and Q structures. We used the Monte Carlo simulation method of Yoshimoto et al. (JGR, 2000) to interpret the estimated relations. Our results indicated that the relations can be explained by depth dependent lm and Q structures: lm and Q are 500 m and 50, respectively, down to a depth of 1000 m, below which lm and Q are 10000 m and 100. The pulse width may be used as a new measure to investigate scattering and attenuation structures at volcanoes.

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Intrinsic Attenuations in the Oceanic Lithosphere and Asthenosphere Constrained by Seismogram Envelopes

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It is widely accepted that the oceanic lithosphere and asthenosphere have high-Q and low-Q, respectively, however, it is not very clear to which extent such attenuations are affected by seismic wave scattering (e.g., Shito et al. 2015, JGR; Kennett and Furumura 2013, GJI). To distinguish the intrinsic and scattering attenuations, analyzing seismogram envelopes is known to be effective. We deployed broadband ocean bottom seismometers on the old Pacific seafloor between 2010-2014 (NOMan Project, http://www.eri.u-tokyo.ac.jp/yesman/). We had quite large number of aftershocks of 2011 Great Tohoku Earthquake and succeeded in obtaining envelopes of Po/So and T-phase at various distances. The data purely sample the old ocean, which should provide unique opportunities to quantitatively constrain the attenuations in the ocean. We applied our envelope simulation method (Takeuchi 2016, JGR) and obtained the attenuation model by grid-searching the best structural parameters to explain the observations.

One of the most unique features of Po/So is that spatial attenuation (i.e., energy loss rate per unit propagating distance) is independent from wave type (P- or S-wave) and frequency (Butler 1987, JGR). Several previous studies (e.g, Sereno & Orcutt 1987, JGR; Mallick & Frazer 1990, GJI) explained such features by slightly ad-hoc attenuation models (strong frequency dependency; larger P attenuations than S). In contrast, we tried to explain the observations without such assumptions and succeeded in explaining most of the observed features. The results suggest that the saturation of backscattering coefficients at higher wavenumbers is primarily responsible for the constant spatial attenuation.

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3D Diffraction Imaging of Fault Zones

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Presented research focusses on seismic analysis of fault damage zones. The statistical modelused based on using fault facies technique. The statistical ensembles of facies spatial distribution are sampled for different values of model parameters. Seismic forward modeling and imaging is performed for each realization. The comparative statistical analysis of original models and the corresponding seismic images is carried out. Our study allows to estimate the potential ability of using seismic methods to analyze the detailed geological structures of subsurface fault zone.
Characterization of faults is a prerequisite for providing reliable assessments of expected flow patterns and trap-integrity in subsurface reservoirs. Fault characterization in specific reservoirs remains highly challenging, as reflected by the substantial literature addressing data handling and modelling of fault-related parameters aimed at capturing and forecasting the impact of faults on fluid flow. The complexity of fault characterization relates both to the nature of the input data available for description as well as the tools and methods used to process this information into models of actual faults.
Faults can be considered as volumetric entities consisting of deformed host rock generated during the faulting process. The products of this process are closely linked to a wide range of parameters, such as tectonic regime, magnitude of fault displacement and mechanical properties of the host rock.
Direct observational data from any individual fault in a subsurface reservoir is either very scarce (i.e. rare cores and well logs through faults), or offers only limited resolution (i.e. physical constrains to seismic acquisition). Thus, characterization of fault properties in sub-surface reservoirs, apart from seismically resolvable geometric relations, is extensively governed by concepts derived from a combination of theoretical considerations and outcrop and laboratory studies.

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Joint inversion for shallow crustal discontinuities from high-frequency waveforms of microearthquakes

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The waveforms of microearthquakes are of high frequency and complicated. They contain many phases secondarily generated at crustal interfaces and at small-scale inhomogeneities. They are highly sensitive to focal mechanisms and thus very different for each station of local networks. However, with a large number of clustered microearthquakes, the reflected/converted waves in waveforms can serve for detecting prominent discontinuities within the crust. With a dense network of sensitive seismic stations and a good azimuthal distribution, it is possible to retrieve a depth of these discontinuities and map their lateral variations. The standard microseismic monitoring is routinely investigated for source parameters; however, an analysis of shallow crustal structure is often missing.

The structure studies based on microseismic data are specific. The depth of discontinuities is modelled using several independent tools provided by refraction and reflections seismics combined with the earthquake source analysis. This includes ray tracing for calculating traveltimes of converted and/or reflected phases, analysis of focal mechanisms and radiation patterns for converted/reflected phases, full waveform modelling using discrete wavenumber method for comparing synthetics with observed data, alignment of traces and their stacking for amplifying studied phases, and grid search for the inversion. Joint interpretation of more phases converted/reflected from the same interface increases the stability of retrieved results and enhances the robustness of the inversion. A novel concept for extracting crustal structure from high-frequency waveforms of local microearthquakes is demonstrated on natural seismicity in the West Bohemia swarm region, the Czech Republic. Clustered seismicity in West Bohemia indicates a strong-contrast interface at depths of 3.5-6.0 km, which is in agreement with previous profiling and might be related to trapping of fluids ascending from the mantle.

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Bias in velocity measurements from ambient noise due to anisotropic source distributions

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Secondary microseismic sources are strong off the Atlantic coast of Norway and dominate ambient noise recorded in Scandinavia. At the same time, the source distribution is quite heterogeneous and sources from the south and east (Baltic Sea) are weak or absent. This source heterogeneity causes significant bias in measurements of velocity of surface waves extracted from ambient noise by correlation. We study this bias effect synthetically and characterize it in terms of Weaver's asymptotic formula at large inter-station distance, r, or short wavelength, L, and in terms of Fresnel angles at short inter-station distance or large wavelength. We find that the bias of group-velocity measurements is significantly higher than that of phase velocity. We find that Weaver's formula applies to within several percent when the ratio $r/L > 10$ and when the local anomaly angular width exceeds the width of the Fresnel angle. When the source distribution varies on a small angular scale and inter-station distances are relatively short the phase-velocity bias can be as large as several percent. We quantify the bias effects of the mapped source distribution around Scandinavia and find that in this region of relatively weak crustal heterogeneity (3%) the bias often exceeds the heterogeneity level, particularly for group velocity. This highlights the need for careful study of the effective source distribution of microseisms and its potential bias effects in regions of weak heterogeneity before inverting dispersion measurements for 3D velocity structure. Phase velocity is to be preferred over group velocity and careful data selection based on the ratio r/L and the azimuthal distribution of the source is vital.

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Approximate vector sensitivity kernels of coda waves to seismic velocity changes based on the scalar single isotropic scattering model

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Coda-wave interferometry has been used to detect velocity changes in association with large earthquakes or volcanic eruptions. Sensitivity kernels of travel times of coda waves are necessary to determine the region of velocity changes correctly. These sensitivity kernels have been formulated so far for scalar waves based on different assumptions of two-dimensional single scattering or multiple scattering, three-dimensional single scattering or multiple scattering, or diffusion. However, no formulation has been made for vector waves as far as we know. Hence, we tackle this formulation and derive analytical approximate expressions for two-dimensional and three-dimensional cases. The key point in our simple extension to vector waves is the projection of seismic phonon energy into horizontal and vertical components by using the square of the direction cosine of the polarization direction. Thanks to this simple idea, we can derive analytical expressions of the approximate vector sensitivity kernels by using the single isotropic scattering model for scalar waves, though we can treat either P waves or S waves at a time. Our results show that the sensitivity kernels are different for different components, and accordingly different components show different travel time changes with respect to lapse time. These are theoretically shown for the first time by this study. The approximate vector sensitivity kernels have two clear peaks at a source and a receiver which are different from different components. Comparing with finite difference simulations of vector wave propagation, we find that our approximate vector sensitivity kernels are very good for two-dimensional cases, but are worse for three-dimensional cases. So far the reason is not clear yet. However, our approximate vector kernels are helpful to consider how to use seismograms of the different components simultaneously in coda-wave interferometry.

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Land-atmosphere coupling and source of low-frequency seismic noise from the analysis of co-located barometers and seismometers

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We studied the nature of coupling between atmosphere and solid Earth by examining co-located seismometers and barometers that are available from many arrays. We summarize a few characteristic features from our analysis of Pinon Flat array in Southern California and Earthscope Transportable Array (TA).

First, we can establish from data that atmospheric pressure at Earth's surface is closely related to winds, basically proportional to square of wind speeds. This pressure in turn causes vertical and horizontal motions in solid Earth. Correlation between pressure and vertical motion is high (correlation coefficient ~ 0.8 or higher), especially for frequencies below 0.05 Hz. This high correlation occurs only above a certain threshold pressure, however (Tanimoto and Valovcin, GRL, 43, 2016). Below this pressure, vertical amplitudes show no correlation with atmospheric pressure. Above this pressure the local atmosphere pressure directly controls vertical motions, showing almost perfect phase-to-phase match in waveforms. Above 0.05 Hz, this correlation starts to become smaller as ocean waves become the dominant source of seismic ground motions.

Horizontal ground motions show quite different behaviors. Horizontal seismic amplitudes change with local atmospheric pressure for the entire range of pressure that barometers can measure. It indicates that ground tilt is the dominant cause of horizontal noise. It is noteworthy that tilt effects on horizontal motions are significant even at low pressure.

Pressure vs. horizontal amplitudes show different (bifurcating) behaviors for many stations between summer and winter. In winter, noise level is always high and is constant in pressure-amplitude plots, meaning local atmospheric pressure is not responsible for seismic motions. But in summer, horizontal amplitudes show good correlation with local pressure changes and show wide variations in amplitudes as pressure changes significantly with time.

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Dominant source locations of secondary microseisms in Japan estimated by Hi-net data

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Microseisms are energetic ambient seismic wavefield generated by ocean swells, which are categorized into primary (10-14 s) and secondary microseisms (5-7 s). Although source locations are crucial for understanding the excitation mechanisms of microseisms, source locations of secondary microseisms still remain uncertain. Moreover, understanding microseism wavefield is important to correctly interpret results of seismic interferometry. In the present study, we estimate dominant source locations of Rayleigh waves in secondary microseisms observed in the Japan islands using Hi-net data. We first estimate back azimuths of Rayleigh waves in the period of 4-8 s based on polarization analysis. Since fundamental Rayleigh waves, dominating secondary microseisms, generally show retrograde particle motions, back azimuth of Rayleigh waves can be determined from three component records at single stations. We then search locations explaining the back azimuth distributions within subarrays in the Japan island. The estimated sources of Rayleigh waves distribute in specific regions. Dominant locations are 100-200 km off the coast of Fukushima and Miyagi in the Pacific, off Tottori in the Sea of Japan, and off the the Shonai Plain. The off Tottori sources show a clear seasonal variation, detected only in the winter season, which is consistent with ocean wave activity in the Japan Sea predicted by an ocean action model WAVEWATCH III. The off Tottori and off Fukushima-Miyagi sources are located at an ocean basin with the depth of 1000-2500 m and at shelf slope with the ocean depth of 2000-6000 m, respectively. The ocean depths are close to the resonance depth for the period of 4-8 s. The off Shonai sources are located in the regions in shallower ocean depth. We consider investigating frequency dependence of source locations may deepen our understanding of mechanism of microseisms.

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Comparison of microseismic Rayleigh and Love waves sources around Scandinavia

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Use of the ambient noise wave field to image Earth structure has extensively increased during the past decade. Information about noise-source locations and their excitation process can be useful for the application of the ambient-noise method and interpretation of its results. The source locations and mechanism of microseismic Rayleigh waves have been studied in many areas. However, few studies have been published about the source distributions and processes of microseismic Love waves. The lack of information about Love wave source locations and their excitation mechanism applies in particular to the secondary microseisms.
An inversion of cross-correlation envelopes over one year (2012) in five sub-arrays of the Swedish National Seismic Network (SNSN) is used to map and compare the azimuthal source distributions of Rayleigh and Love waves within the primary and secondary microseisms around Scandinavia. The results from all sub arrays can be combined to map the potential source locations of the Rayleigh and Love waves. Comparison of the source locations of the two waves types indicates that Rayleigh and Love waves within the primary microseismic band arrive from similar directions, whereas in the secondary microseismic band the source locations are not always co-located. Our results suggest that most of the energy of the secondary microseisms originates in near-coastal areas (mainly along the western coast of Norway), and could be related to channel-shaped features in the ocean bottom bathymetry. Also, the dominant source locations of different period ranges of the secondary microseisms varies, especially for the Love wave.

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Global source location of P-wave microseisms using Hi-net data from 2005 to 2011

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Source locations by a back projection method is feasible for understanding the excitation mechanism of secondary microseisms. However, complex wave propagations of surface waves caused by strong shallow, lateral heterogeneities prevent from the precise location of the sources. In contrast, body wave microseisms are less scattered than the surface-wave microseisms. Although the amplitudes of body wave microseisms are smaller than surface wave amplitudes, recent developments in source location based on body-wave microseisms enable us to estimate precise locations of forcing and the amplitudes quantitatively [e.g. Nishida and Takagi, 2016]. In this study, we made a catalogue of P-wave microseisms by array analysis using the Hi-net operated by NIED from 2005 to 2011. We analyzed vertical-component velocity-meters with a natural frequency of 1 Hz at 202 stations in Chugoku district. The instrumental response was deconvolved by using an inverse filtering technique after reduction of common logger noise. The records were divided into segments of 1024 s. After exclusion of segments which include transients, the frequency-slowness spectra were calculated. The spectra at 0.15 Hz show that clear teleseismic P-wave microseisms on seismically quiet days when local swell activities were calm. The local maxima of the spectra were picked up. The centroids of the sources were located by backprojecting the corresponding slowness. The source locations show clear seasonal variations. In winter months, they were located in the northwestern Pacific, and in the summer months they were located in the southern Indian ocean. Through the years, centroids stayed in the north Atlantic ocean, although they show a weaker seasonal variation with the maximum in winter. The locations can be explained by an ocean action model (WAVEWATCKIII: Ardhuin et al. 2011). In further studies, we will calculate the equivalent vertical single force for quantitative discussions.

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Quantifying the body-wave information retrieved from global earthquake coda correlation

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Body wave retrieval from noise or coda correlations provides sampling at greater depths and has advanced our ability to probe and monitor the deep Earth. However, to date the identification of body waves in correlations relies mainly qualitatively on the signal-to-noise ratio of phases and the matching of theoretical travel times and lacks a quantitative validation of their travel-time accuracy and spatial sensitivity. Based on recent observations that the late coda of large earthquakes is not diffuse and that the source locations of the large earthquakes used in coda correlations are well known, it becomes viable to approach the question through numerical simulation with spherically symmetric Earth models (no scattering) for coda correlation. By varying numerous parameters such as source duration, source distribution, and velocity/Q structure, 143 global large earthquakes (Mw7) and USArray stations are used to compare with and to validate the observations of recently-reported core phases (e.g. P'P') from coda correlations (Huang et al., 2015). Simulation results show that using only reverberations can replicate most of the features of the body-wave signals observed in correlation functions. The travel time bias present in the (zero-offset) autocorrelation functions is insignificant (within 0.5 s) as long as the selected coda windows are sufficiently late (after ~10000 s) while the bias in cross-correlation functions shows a systematic trend that increases with station separation regardless of source distribution. With the aid of ray-based modeling, we explore the mechanism of such bias, the emergence of spurious phases, and distinct frequency content between coda and noise correlation. Gaining a better understanding of such body-wave information improves our ability to use and validate correlation-based data, making it possible to reliably integrate such measurements with earthquake-based data in future applications.

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Illuminating the Cascadia forearc and Mendocino Triple Junction system from seismic interferometry

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We use autocorrelation to extract the reflection response from the coda of transmitted P-waves from distant earthquakes recorded at dense seismic arrays in the western US (Cascadia 93 and FAME Mendocino experiments). This results in two 300 km-long reflectivity profiles across the forearc and arc of the Cascadia subduction zone in Oregon and northern California. The results show good agreement with prior knowledge of the forearc based on inverse scattering and multi-mode conversion imaging, including the presence of a dipping low-velocity zone (LVZ) from 20 to 40 km depth near the plate interface. From observed data and numerical modeling with spectral element methods, we investigate how the quality of the reflection response obtained from P-coda autocorrelation is influenced by the distribution of earthquakes and the complexity of the transmitted wavefields. We also illuminate more precisely the uppermost 100 km of the mantle in the transitional domain from subduction to transform regimes in the Mendocino Triple Junction system. We find that the LVZ extends from the subduction regime at North to the transform regime at South as far as the Clear Lake volcanic field (38.97 degree North; 122.77 degree West). We speculate the existence of a portion of the Gorda plate near 60 km depth in the transform domain below this same volcanic field. Our results raise questions on the nature of the LVZs, their relationship to non-volcanic tremors in the subduction and transform regimes of the Mendocino and San Andreas regions, and on the presence of remnants of fossil slabs attached to the Pacific plate underneath the edge of the North American plate.

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Retrieval of tsunamis by the interferometry of deep ocean pressure records

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Ocean surface waves are ubiquitous and incessant. We applied the waveform interferometry to the records from deep ocean pressure gauges to retrieve tsunami waveforms without tsunami sources.

Continuous pressure records for the year 2011-2015 from three tsunami-meters operated by NOAA, located along the western boundary of the Pacific at the depth of 5500-5900 m were used for the tsunami interferometry. Distance between stations ranges from 956 to 2265 km. De-tided data were processed to enhance the cross-correlations. The stacked waveform showed gradual amplitude increase toward the arrival time of virtual tsunami propagating between two stations. A sharp transition from positive to negative amplitude was observed at the expected arrival time.

This characteristic waveform reflects the fact that the long-wave tsunami at the deep ocean is nearly non-dispersive for a broad wave-period range. In theory the cross-correlation of 2D isotropic non-dispersive wavefield coming from large distance shows a gradual increase of amplitude before the expected arrival time of the virtual waves traveling between two points. No plane wave arrives at two points with a time lag larger than the traveltime between the two points, corresponding to the abrupt amplitude decrease of cross-correlated waveforms. In reality dispersive surface gravity waves propagate at speeds slower than long-waves and appear later than the virtual tsunami.

The extracted virtual tsunami waveforms were then analyzed for the phase velocities of tsunamis between two points. Subtracting the initial phase from the measured phase by assuming cylindrical 2D waves, we succeeded in measuring the phase velocity of virtual tsunamis for the period range from 300 to 3000 s. The measurements were in good agreement with the tsunami phase velocities expected from the ocean depth. A clear reduction of phase velocity from long-wave speed, as predicted from the surface gravity wave theory, was detected for wave periods near 300 s.

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HV Spectral Ratio (HVSR) for preliminary seismic characterization of Sun Pyramid in Teotihuacan, Mexico.

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Currently Teotihuacan is one of the most important archaeological sites in Mexico and it is the most representative city of the classic period in the central Mexican anti-plane. In the center of Teotihuacan two monumental structures stand out: The Moon and the Sun pyramids. The latter is the largest structure. With the purpose of knowing its seismic characteristics and constructive processes of the Sun Pyramid, we carried out a campaign of environmental seismic noise measurements with 16 sensors distributed in the different locations and levels of the pyramid. In this work we show some preliminary results of the HV Spectral Ratios (HVSRs) which show a clear effect of amplification in different frequencies for the different levels produced by the existence of irregular geometry. Also, we will focus on the directionality of HVSRs in order to understand the topological effect and the heterogeneity within the pyramid.

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Crustal Structure of South Yogyakarta Area Revealed By Spatial Auto Correlation and Ambient Noise Tomography

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The 2006 Yogyakarta earthquake struck the Indonesian island of Java with Mw 6.3 on May 26, 2006 that caused major damage and thousands of deaths in the area of Yogyakarta and Central Java province.Based on the aftershocks recorded by temporary seismic network deployed shortly after the earthquake disaster, the source of the 2006 earthquake was located about 20 km east of Opak fault. However, detail structure of 2006 earthquake's fault remains unclear. Its vicinity to highly populated Yogyakarta brings a reasonable motivation to investigate this geology structure and its potential hazard further. Until 2016, several weaker earthquakes were still felt by residents living around Opak fault and 2006 fault zone. To follow up this case, Gadjah Mada University and the Institut de Recherche pour le Developpement (IRD) conducted a seismic measurement around the faults area from October 2015 to May 2016. The purposes of this measurement were to determine the detail structure of the fault and to obtain velocity model of subsurface (YOG ver 1.0) using Spatial Auto Correlation (SPAC) and Ambient Noise Tomography (ANT) method. Data acquisitions were carried out on the west side and the east side of the fault zone to map lateral velocity variation. Shear wave velocity, Vs contrast obtained by this measurement clearly indicates Opak Fault and 2006's fault zones which also reflects different types of lithology. This result improves the accuracy of local earthquake relocations and provides better images of local structures in Yogyakarta area. Through this research a processing software for Ambient Noise Tomography (GAMANT) also has been developed. As the measurement around Opak fault and 2006 fault zone shows very promising results, another experiment in Merapi will also be conducted this year to investigate the possible relation between crustal fault and volcanic activities.

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Surface wave tomography of Java Island from ambient seismic noise

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P- and S-wave velocity structures beneath the Sunda Arc, including Java Island, were successfully imaged in our previous studies using a global data set and a nested regional-global tomographic method. To obtain detailed crustal structure information of the region beneath Java, we have since employed the Ambient Noise Tomography (ANT) method. In this study, we have used seismic waveform data from MErapi AMphibious EXperiment (MERAMEX) in central Java and those recorded by BMKG stationary seismographic stations in Java and 25 portable seismographs, which were installed for 2 to 8 weeks in eastern and western Java. The data have been processed to obtain waveforms of cross-correlated noise between pairs of seismographic stations. Our preliminary results, for example, indicate that the Kendeng Zone, an area of low gravity anomaly extending from central to east Java, is associated with significantly lower seismic velocity than average. On the other hand, the southern mountain range, with a high gravity anomaly, is related to a high seismic velocity anomaly. We are now in the process of finishing data acquisition in western Java. The expected ANT imaging results of the whole of Java Island will be presented in the meeting. For future work, we will combine the ANT result with the mantle velocity models using body wave tomography to obtain accurate locations of earthquake hypocenters and to construct regional tectonic structures in unprecedented detail. Both of these are vital for understanding seismic hazards in Java, which is one of the most densely populated islands in the world.

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Depth dependence of stress sensitivity of seismic velocity changes as inferred from noise correlation analyses at Izu-Oshima volcano, Japan

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We determine stress sensitivity of seismic velocity changes at Izu-Oshima in Japan based on a seismic interferometry method. Ambient noises recorded at four seismic stations deployed on the small volcano island for 4 years from January 2012 to December 2015 are used to calculate cross correlation functions. Cross correlation functions are estimated at frequency bands of 0.5-1Hz, 1-2Hz, and 2-4Hz. Applying a moving window time analysis to the cross correlation functions, we estimate daily seismic velocity changes. Decrease and increase of seismic velocity changes are well associated with the areal strain changes observed by GNSS network. Comparing the areal strain changes with seismic velocity changes, we calculate the stress sensitivity of seismic velocity changes to be (7.1+/-1.3)x10-8 Pa-1 at the frequency band of 0.5-1Hz, (1.4+/-0.1)x10-7 Pa-1 at 1-2Hz, and (1.3+/-0.1)x10-7 Pa-1 at 2-4Hz, respectively. The stress sensitivity of seismic velocity at 0.5-1Hz is lower than those at the higher frequencies. The observed seismic velocity changes are located in the upper 1 km by assuming the wave length of Rayleigh-wave. The result at Izu-Oshima is consistent with the stress sensitivity of seismic velocity changes by previous studies. We conclude, therefore, that the stress sensitivity of seismic velocity changes decreases with depth down to a few kilo meters, which is probably due to the increase of confining pressure.

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Observation of coseismic and postseismic velocity changes for deep borehole seismic stations in the Kanto area

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Using Passive Image Interferometry (PII), we analyze long time series of seismic noise data from Hi-net seismometers in the Kanto Basin in and around Tokyo. The 17 deep borehole seismometers used in this study are located in depths between 1200 and 3500 m below the Earth's surface. The analyzed time series span 9.5 years (January 2003 to June 2012) and include the recordings of the MW 9.0 Tohoku-oki earthquake on 2011 March 11 and also an M 5.7 earthquake in Southern Ibaraki prefecture on 2004 October 6.
Single-station cross-correlations and cross-correlations were calculated for the different stations and station pairs, respectively, in frequency ranges between 0.125 and 4.0 Hz. Significant coseismic velocity drops are observed, followed by postseismic recovery that can be modeled by an exponential function. Using the frequency-dependence of the velocity changes, we can constrain the depth range of the observed velocity changes. Furthermore, we correlate the observed velocity changes with the pga and pgv values at the respective sites.
As this study uses very deep sensors compared with previous studies, we anticipate that the observed noise field differs from the one observed at surface stations. Consequently, the depth range of the observed coseismic velocity changes can be constrained more precisely combining the results of this study with previous results.

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Monitoring volcanic and geothermal fields using seismic noise: the case study of the Las Tres Virgenes geothermal field (Mexico).

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Volcanoes are known to be dynamic systems where physical properties change over the time because of the magma ascending into de main and secondary conduits that produce variations of stress on the edifice and in the crust. Geothermal systems under exploitations are often compared to volcanoes because re-injection of fluids in depth through wells may create small perturbations of the field that can also generate induced seismicity.
In the last decade the analysis of large records of seismic noise allowed to retrieve useful information about the non-stationary condition of the physical properties of volcanoes with the aim to develop efficient forecasting eruption models. First attempts to detect seismic velocity variations during injections also showed that the seismic noise monitoring might be use to observe and describe such variations over the time.
In this work we show how the seismic noise correlation technique can be applied to monitor changes on seismic velocities into a geothermal field operating in a volcanic region, and which are the observables originated by the power plant activities and those related to the natural activity of the area.

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Anisotropic S-wave velocity change in the shallow subsurface associated with the 2016 Kumamoto earthquakes

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In this study we focus on anisotropic S-wave velocity change at KiK-net station KMMH16, where PGV exceeding 100 cm/s was recorded when the 2016 Kumamoto earthquake, Japan, occurred. We use 217 earthquake waveforms registered by station KMMH16, where S-wave coda is used to avoid apparent velocity change due to difference in incident angles. After correcting azimuthal bias, we rotate two horizontal components every 10 degree for both surface and borehole bottom (255 m depth) records to compute polarized waveform pairs. Then we deconvolve the polarized waveform on the ground surface by that at the borehole bottom to extract Green's function between the two sensors. After applying 4-20 Hz bandpass filter to the deconvolved waveform, we apply the stretching technique using lag-times of 0.2-0.9 s to extract relative velocity change before and after the Kumamoto earthquake for each polarization direction.
In the period within 7 minutes to 26 hours after the MJ6.5 foreshock on April 14, we find the maximum velocity change of -7.0% for N50E polarization direction, while the minimum velocity change is -3.6% for N10W direction. The N50E direction is close to the along-strike direction of the Futagawa-Hinagu fault system. Within 53 minutes to 14 hours after the MJ7.3 mainshock on April 16, the velocity further reduce to -7.4% for N50E direction. The velocity recovers to -4.8% by two months after the mainshock, while no further recovery is found within 2-9 months after the mainshock.

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Spatio-temporal changes of seismic scattering properties associated with the dike intrusion on 15 August 2015 at Sakurajima volcano, Japan, detected by seismic interferometry

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Seismic interferometry has been used to detect spatio-temporal changes of seismic scattering properties (e.g. Obermann et al. 2013a). At Sakurajima, one of the most active volcanoes in Japan, a dike intrusion took place on 15 August 2015, and large ground deformation was observed (e.g. Hotta et al. 2016). Such a dike may work as a new scatterer for seismic waves. Therefore, we applied seismic interferometry to detect changes in seismic scattering properties associated with this event. We used the vertical components of ambient seismic noise data at 1 – 2 Hz recorded at 6 JMA stations from 1 January 2012 to 31 August 2015. We calculated coherences between reference CCFs (stacked over 2012 and 2013) and daily CCFs, and found that all station pairs showed significant decreases of coherences before and after the dike intrusion. To locate the region where the seismic scattering properties changed, we used sensitivity kernels calculated from 2D radiative transfer model. Parameters of scattering and intrinsic absorption that are needed to calculate sensitivity kernels were estimated by modeling the space-time distribution of energy density of active shot records. The best-fit parameters were as follows: Mean free path of Rayleigh waves was 1.2 km at 1 – 2 Hz, and intrinsic absorption Q was 62.8f (f is the frequency). Then, we calculated the differences between mean values of coherence in 2014 and those of from 16 August 2015 to 31 August 2015 (hereafter ΔC). Assuming that one seismic scatterer appeared on the surface projection of the dike, we searched the best location of the scatterer to explain observed ΔC. That was located at the same place as the dike determined by using geodetic data (Hotta et al. 2016) with an accuracy of about a few km, and the change of scattering coefficient (Δg) was estimated as 1.4 km-1. Acknowledgements: We used seismograms recorded by JMA. Active seismic experiments were conducted by DPRI, Kyoto University, other 8 universities, and JMA.

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Characterization and monitoring of ambient vibrations of a rock slope close to collapse

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We present the ambient vibration study of Alpe di Roscioro, a developing rock slope failure located above the village Preonzo in southern Switzerland. Following a major failure in May 2012 (volume ˜210,000 m3), the remaining unstable rock mass (˜140,000 m3) remains highly fractured and disrupted, and has been the subject of intensive monitoring. A small-aperture seismic array was deployed at the site shortly after the 2012 failure. The measured seismic response exhibited strong directional amplification (factors up to 35 at 3.5 Hz), higher than previously recorded on rock slopes. The dominant direction of ground motion was found to be parallel to the primary direction of deformation and perpendicular to open fractures, reflecting subsurface structure of the slope. The site has been later equipped with two semi-permanent seismic stations to monitor changes of the seismic response due to internal damage that may precede subsequent failure. Although failure has not yet occurred, our data reveal significant variations in the seismic response. Resonant frequencies exhibit seasonal trends related (both directly and inversely) to temperature changes, and are sensitive to freezing periods (resonant frequencies increase with temperature and during freezing).

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Separation of intrinsic attenution and scattering loss for the contiguous US

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We invert 10 years of earthquake envelopes registered by the USArray to construct maps of S-wave intrinsic and scattering attenuation of the crust beneath the contiguous US in the frequency range 1 Hz to 20 Hz. We also report site amplification factors and a comparison of estimated moment magnitudes with Richter magnitudes determined by the Array Network Facility (ANF). We observe a distinct west-east decline of intrinsic attenuation for high frequencies corresponding to the west-east transition from young, hot rocks to old and cold rocks. Scattering loss on the other hand depicts a raising west-east trend, but generally has a higher spatial variation than intrinsic attenuation. The crust in the western part of the United States appears to be more homogeneous on the relevant length scales than the crust in the eastern part.

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Spatial variations of intrinsic absorption and scattering loss in Taiwan based on a Multiple Lapse Time Window Analysis

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We use seismic recordings from 2012 to 2015 to estimate intrinsic absorption and scattering loss in Taiwan. Signals were recorded by a network of about 150 stations. About 400 events of magnitude between 3.5 and 6.5 and 4000 events of magnitude between 1.8 and 3.5 were recorded per year. We use the Multiple Lapse Time Window Analysis introduced by Fehler et al. (1992) to measure integrals of energy in different windows in the coda of the signals, selecting events with hypocentral distances below 100 km and sources less than 40 km deep. These measurements, which represent the temporal distribution of the energy in the coda, can be used to separate the two components of attenuation, absorption and scattering. An inversion using a Levenberg-Marquardt algorithm is performed to find estimates of the absorption and scattering quality factors Qi-1 and Qsc-1, for each station considered. We find that Taiwan is one the most highly attenuating regions in the world, with an average of Qsc-1 = 1e-2 and Qi-1 = 7e-3 at 1-2 Hz. Another important feature is that attenuation varies widely across Taiwan, by a factor of 3 for total attenuation. We find that the eastern Coastal Range and parts of the western Coastal Plain are the most highly attenuating regions of Taiwan. However, the region surrounding the Peikang Basement High and parts of northern Taiwan are more weakly attenuating, which increases risk for the cities in this region. Overall, intrinsic absorption is more uniform than scattering loss. The Coastal Plain shows strong scattering. The Coastal Range shows strong scattering and absorption, consistent with the volcanic origin of the structures. Scattering in the Central Range seems weaker than in these two regions. Our study shows that attenuation should be taken into account for seismic studies and monitoring in Taiwan, given the importance and lateral variability of the mechanism.

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Significant anomalies in high-frequency seismograms for intra-slab earthquakes observed in Kanto area, Japan: Importance of mode-conversion scattering

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In Kanto-Tokai area in Japan, very complicated high frequency seismograms are frequently observed as it is located above a complex subducting zone. In this study, we found characteristic high-frequency seismogram anomalies potentially being related to characteristic inhomogeneity in this area.

We analyzed Hi-net (NIED) records in Kanto-Tokai area for 20 intra-slab earthquakes (M4.4–6.9) occurred within the Pacific slab from October 2004 to April 2016, 227–453 km in depth. After applying bandpass filters of octave bandwidth of 1–16 Hz, characteristic wave packets were identified from root mean squared (RMS) envelope seismograms. At a frequency range of 8–16 Hz in Kanto area, we found wave packets preceding the arrival of S waves by about 10 s. At lower frequency of 1–2 Hz, we did not find similar packets. The amplitude of the packet was always predominant in the vertical component. No strong polarization in the horizontal component RMS envelopes is observed.

Complicated-shape wave packets lasting about 10 s, without significant pulse of boundary conversion, suggest that scattered wave packets are generated by the small-scale inhomogeneities. In addition, this cannot be explained by a simple S-to-S scattering because of its arrival time. Based on the systematic detection, we found that the wave packet propagated almost along the radial direction from the epicenter with the same apparent velocity as that of the S waves. Considering the wave packets arrived earlier than S waves, they are expected to involve mode-conversion such as P-to-S or S-to-P scattering generated by characteristic inhomogeneity between the epicenter and seismic stations.

Preliminary numerical simulations of seismic wave propagation in this area with superimposed onto a small-scale stochastic velocity fluctuation did not explain these peculiar wave packets. Considerable updates especially for small-scale inhomogeneities are expected to contribute to further understandings of the subduction zone.

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Amplitude fluctuation of seismic waves in the crust

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The amplitudes of high-frequency P- and S-waves generated by local earthquakes vary from site to site, even at similar hypocentral distances. It had been suggested that, in addition to non-isotropic source radiation and local site effects, complex wave propagation in inhomogeneous crust is responsible for this observation. To quantitatively investigate this effect, we performed observational and numerical studies on the amplitude fluctuation of P- and S-waves in inhomogeneous crust. Using seismic data from 31 small-to-moderate crustal earthquakes that occurred in western Honshu, Japan, we measured the fluctuation in maximum velocity amplitudes observed by the borehole seismometers of the NIED Hi-net. Observed maximum velocity amplitudes of P- and S-waves in the frequency bands of 1–2 and 2–4 Hz were normalized on the basis of the coda normalization method. Other technical details are same as in Yoshimoto et al. (2015). Our observations of P- and S-wave amplitudes (coda-normalized maximum velocity amplitudes) revealed that fluctuations in P- and S-wave amplitude increase with increasing frequency and hypocentral distance, with large fluctuations showing up to ten-times difference between the largest and the smallest amplitudes. It was found that the standard deviation of amplitude fluctuation of P- and S-waves increases monotonically in small hypocentral distances; however, the increase tends to become saturated at a hypocentral distance of tens of kilometers. Our numerical simulation via finite-difference method indicated that the observed characteristics of amplitude fluctuation can be explained by crustal inhomogeneity stochastically characterized by an exponential random model with a correlation length of about one kilometer and standard deviation in seismic velocity of a few percent.

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Shallow S-Wave Velocity Structures of the Northern Taichung Area, Taiwan, Using Microtremor Array Data

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Shallow S-wave velocities have widely been used for earthquake ground-motion site characterization. We investigate the shallow S-wave velocity structures at the northern Taichung area, Taiwan by using the array records of microtremors at 24 sites. The dispersion curves at these sites are calculated using the F-K method (Capon, 1969); then, their S wave velocity structures are estimated by employing the surface wave inversion technique (Herrmann, 1991). At most sites, the observed phase velocities are almost flat with the phase velocity of about 1000 m/sec in the frequency range from 0.5 to 2 Hz. This suggests that a thickness layer with an S-wave velocity of about 1100~1400 m/sec was deposited. If the S-wave velocity of the Tertiary bedrock is assumed to be 1500 m/sec, the depths of the alluvium at the northern Taichung area are between 270 m and 1400 m. The depth of the alluvium gradually increases from east to west. The S-wave velocity decreases from east to west while the depth is larger than 400 m at the area.

Comparison three applications of microtremor analysis for investigating shallow S-wave velocity structure in the Western plain of Taiwan

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We had conducted forty-five array measurements of microtremors and applied GA-Haskell calculation for more than one thousand microtremors H/V measurements in order to investigate the shallow S-wave velocity structure in the Western plain of Taiwan. The microtremor array measurements are reliable to obtain shallow velocity S-wave structure. However, the interval of measurement is about 15 km due to the limitation of economic and manpower issue. GA-Haskell method applies for one thousand microtremors H/V measurements so as to improve the survey interval to about 2 km. Nevertheless, the velocity structure calculated by GA-Haskell method is difficult to quantify the misfit. Hence, we utilize the H/V inversion approach to the same sites of microtremors measurements. The objective of this study is to compare three different methods and figure out the skill of three methods in estimate the shallow velocity. The suspension PS-logging profiles are using to validate our calculations. After the verification, the Horizontal-to-vertical spectral ratios of microtremors (MHVRs) are hence applying to investigate the shallow S-wave velocity structure in Taiwan.

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Elastic Velocity Change associated with the 2016 Kumamoto Earthquakes, Japan

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A seismic interferometry analysis of the Hi-net seismograms found temporal change of subsurface velocity structure after the 2016 Kumamoto earthquakes. Significant velocity decreases (-6.0 - -0.5 %) were detected near the main shock fault by the analysis of ambient noise auto correlation function (ACF) with the lag time of 4-15 s. The large ground acceleration (> ˜100 cm/s/s) and the large volumetric strain (> ˜-5x10^-6) were observed at these stations where the velocity decreases were found. We also analyzed the ACFs with the lag time of 1-5 s and found velocity increase and decrease around the fault. A station N.MSIH near the fault shows velocity increase. Fukuyama and Suzuki (2016) estimated large compressional strain at the N.MSIH station by analyzing permanent vertical displacements recorded at two acceleration sensors deployed different depths. The compressional strain change may cause the velocity increase of N.MSIH. On the other hand, when we analyzed the ACF at the lag time of 4-15 s, velocity change was not recognized due to unstable behavior of the ACFs. The dependence of the velocity change on the lag time suggests that the velocity change considerably varied in space. The velocity increase associated with the earthquakes may reflect localized strain change near the main rupture. High-density observation around the focal area enabled us to detect the localized velocity increase after large earthquakes.

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A temporal and spatial change in seismic velocity caused by the 2016 Kumamoto earthquake using cross-correlations of ambient seismic noise.

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Revealing the damage of seismogenic faults caused by earthquakes is important to understand the condition of the seismogenic faults and to predict the seismogenic fault behavior.In recent years, some researches demonstrate that the seismic velocity change at the large earthquake is associated with variation of subsurface stress and crust damage.To estimate temporal variation of the subsurface associated with the 16 April 2016 Mw 7.1 Kumamoto earthquake, we estimated spatial and temporal variation of seismic velocity by using ambient seismic noise recorded by a high-sensitivity seismograph network (Hi-net) for a year of December 2015 to November 2016. We computed cross-correlations of ambient seismic noise records to retrieve virtual seismogram propagating between the pair of stations, and applied the stretching interpolation technique to estimate the temporal change in seismic velocity. Our results show that the seismic velocity near the Futagawa-Hinagu fault zone and volcanic regions clearly decreased at the Kumamoto earthquake. The velocity reduction near the fault zone (˜0.4%) could be occurred due to the damage of the fault. The largest seismic velocity reduction observed around Mount Aso (˜0.8%) might be caused by pressurized volcanic fluids. Furthermore, the decrease in seismic velocity gradually returned to the pre-earthquake value, suggesting gradual healing of the damage caused by the earthquake.

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Temporal change of subsurface structure near Mt. Aso inferred from seismic interferometry using V-net vertical array data

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It is important to monitor the temporal change of the seismic velocity related to the volcanic event. In this study, we estimated the temporal change of subsurface structure in the Aso region with seismic interferometry (SI). In this study, we analyzed the data recorded from Jan. 1, 2015, to Oct. 31, 2016, at 4 V-net stations deployed by National Research Institute for Earth Science and Disaster Resilience (NIED) around Mt. Aso. Each station is composed of a broadband seismometer at the surface and a high-frequency seismometer (1 Hz) at the bottom of a borehole (depth ~200 m). First, the records were bandpass-filtered from 2 to 8 Hz. After 1-bit normalization and spectral whitening, a daily CCF between the same component of the bottom and surface sensors was calculated. Then, we made a reference CCF to stack CCFs from Oct. 25 to 31, 2016. Second, we measured the delay times in time windows of 2.56 s whose center time was increased from -5 s to 5 s every 0.2 s. When the temporal change is homogeneous, the slope characterizes the bulk velocity change within a spatial scale of about 2 km, and the intercept characterizes the localized velocity change between the sensor pair (~200 m). After the 2016 Kumamoto Earthquake, in the NS component at Takamori station and the ES station at other stations, the estimated slope showed the velocity reduction of approximately 0.2 %. On the local velocity change in the borehole, nearly 5-8 % velocity drop was observed at 3 stations except for Nagakusa station. Otherwise, there was an approximately 20 % drop at Nagakusa station. This could attribute the serious damage on the station of the subsurface structure by the earthquake. At Ichinomiya station, the velocity change with the time scale of a few weeks was detected. This change was well agreed with a simple model of the ground water level inferred from the data, and could be localized near the borehole because the station is in a volcanic alluvial fan.

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Seismic velocity variation within the Tatun Volcano Group, Northern Taiwan, from ambient noise analysis

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The Tatun Volcano Group (TVG) locates in the north part of Taiwan, where is only 15 km away from the downtown Taipei. Thus, the monitoring for the potential activity of volcano is required for geohazard assessment. Up to now, more than forty broadband seismic stations have been installed in the TGV area to monitor the micro-earthquakes and the specific singles related to hydrothermal system. Such dense seismic network with long-term continuous seismic data would provide the information to study the temporal or spatial change of properties of the TGV. In the study, we use correlation of ambient noise between stations to determine the temporal variation among 2013 to 2015. The seismic velocity variations show comparable pattern with the anomalies of geochemical observations related to ML 4.0 Shilin earthquake. Significant velocity reduction was observed by the nearby interstation path and HCl concentration rapidly increased. Additionally, we also compared the temporal/spatial seismicity with the velocity variation.

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Study of repeating events in the Jalisco subduction zone, Mexico

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Low Frequency earthquakes (LFEs) as well as repeating low amplitude regular earthquakes are both observed in the Jalisco subduction zone, Mexico. We use the “Mapping the Rivera Subduction Zone" (MARS) seismic array, which is a large array of 51 stations located in Jalisco, Colima and part of Michoacan, to detect and locate them. This is done in both cases with a matched filter search (Frank et al., 2014). The templates for the repeating earthquakes are found by stepping through 10s windows and cross-correlating those with the rest of the data stream on a single station. High correlation coefficients that match in time with other stations are found to be events/templates. These templates are then used in the matched filter over the array spanning at least eight months. The LFEs are much smaller than the regular earthquakes. In order to find them, specific move-outs are used by grid searching in zones where tectonic tremor (TT) has previously been found. Nonetheless, the detection of LFE's has been difficult and do not match TT activity in the zone so far. The main reason for this is that few LFE templates above the TT background signal have been observed.

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The study of the high-frequency microseismic noise at the Russian Platform

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Passive seismic imaging is based on coherent signal allocation in the measurement results of seismic noise of two receiver stations. Numerous theoretical studies and numerical simulations have shown that the cross-correlation of seismic noise determines the source function (Green's function), which describes the propagation of surface waves between two receiver-stations. Rayleigh surface waves with weak damping is widely used by researchers to construct the deep structure of the geological environment with the help of the cross-correlation techniques. Studies show that body waves give a substantial contribution for high frequencies. However, the contribution of energy and the distribution of noise sources define frequency range and conditions of the measurement, which is especially important for high-frequency seismic noise in the area for which the noise is largely man-made. The paper studied the composition of seismic noise in the range of high frequencies at the Russian Platform, which is characterized by thick deposits of loose sediment, as well as a high level of anthropogenic interference. This work was supported by the Russian Federation Presidential Program for State Support of Young Scientists (project no. MK-2698.2017.5).

*S04-1-01
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Revision of the world's best-known recurrence pattern of historical subduction earthquakes along the Nankai trough off southwest Japan and their relationship with large inland earthquakes

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Nine series of M 8-class interplate earthquakes, whose recurrence is a nationwide concern, have been recognized along the Nankai trough off SW Japan; in 684, 887, 1096/99, 1361, 1498, 1605, 1707, 1854 and 1944/46. For deeper understanding of their recurrence nature I reevaluated their space-time pattern in a careful historiographical manner. Some examples of discussions are as follows. On the 684-887 interval, a historian supposed an earthquake in 794 based on an ancient document. But, by critical reading of the document I strongly suggest that this event was a thunderstorm. As for the 1096/99 series it has been considered that the 1096 event occurred in the east and the 1099 one followed in the west. The latter, however, has no evidence of a great earthquake except for an inferred coseismic subsidence in Shikoku, while the former has various evidence of a great earthquake. I examined the only material referring to the subsidence in Shikoku, and clarified that it had originally been written about 80 years after the earthquake and probably duplicated around 100 years later, suggesting unreliability of the 1099 subsidence. I interpret that the 1099 event was an inland earthquake and the 1096 event was an “entire-Nankai trough" earthquake. Regarding the 1605 event, though I had once proposed an idea that it had been a great tsunami quake along the Nankai trough, which has been widely accepted, I reexamined historical documents in the early 17th century thoroughly and propose a new view that the 1605 event was a great earthquake along the Izu-Bonin trench, referring to the 2010 off-Bonin earthquake, and that the Nankai trough earthquake of this series was the 1614 event so far commonly regarded as an inland earthquake. I also discuss remaining problems and the relationship between Nankai trough earthquakes and large inland earthquakes, and propose a seismotectonic model attaching importance to the Amur plate motion in addition to the Philippine Sea plate subduction.

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A possible tsunami caused by a submarine landslide in 1512 at the Nankai trough, Japan

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“SHINCHO-KI" is an ancient document that records tsunami damages caused by the 1512 Eisho earthquake, the 1605 Keicho earthquake, the 1707 Hoei earthquake and the 1854 Ansei-Nankai earthquake at Shishikui region in Tokushima, where is located along the coast of the southeastern part of Shikoku, facing to the Nankai trough. According to SHINCHO-KI, 3700 people were dead at Shishikui by the tsunami during the 1512 Eisho earthquake. However, no evidence was found for the occurrence of 1512 Eisho earthquake except for SHINCHO-KI, while the other earthquakes were recorded in many ancient documents in the southwestern Japan.
To investigate the source mechanism of the 1512 Eisho earthquake, we carefully read a bathymetric chart and found a scarp with height of about 400 m and width of about 6000 m at a position about 24 km offshore in the southeastern direction from Shishikui. We also carried out a survey by using a deep-towed sub-bottom profiler (SBP) on ROV NSS during the R/V Hakuho-maru KH-16-5 cruise. The result shows detailed structures possibly caused by a recent landslide. The vertical displacement of the strata was measured to be about 50 m. By considering these results, we simulated the 1512 Eisho tsunami generated by a submarine landslide. The topographic data in Shishikui which is needed in the calculation was made from the present data. But we removed the artificial structures such as wave breakers and altered costal lines by referring to old map images. The numerical simulations indicated that the tsunami flow depths during the 1512 Eisho tsunami described in SHINCHO-KI could be simulated by the assumed submarine landslide. The maximum tsunami height of 9 m was calculated at Shishikui, while it was 3 m along the Kii Peninsula located at the opposite side of the Kii Channel.

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Hot Spring Anomalies Observed in Kumamoto Prefecture Associated with the 1946 Nankai Earthquake

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Kumamoto-Ken Saii-shi (Record of natural disasters in Kumamoto Prefecture) published by the Kumamoto meteorological station in 1952 describes the 1946 Nankai earthquake in the chapter for earthquakes, "No. 242, December 21, Showa-21: Great earthquake in the Nankai area. The hypocenter is south of Kii (Wakayama Prefecture). There are anomalies in groundwater at many hot springs." (Only related descriptions are extracted and translated here). The anomalies are summarized in a table. The hot springs where anomalies are observed are located in the areas corresponding to Hitoyoshi, Kumamoto, Amakusa, Yatsushiro, Tamana, Minamata and Oguni, using the present location names. The conditions or changes in flow rate, color, and temperature are listed for 15 hot springs. The times of the changes at the hot springs varies from December 23, 1946 to January 6, 1947. The observation periods are from several days to about a half month. The changes in flow rate, both increases and decreases, began on the day of the earthquake and continued over 10 days for most hot springs. The color changes were observed for 10 hot springs. The color changed to light brown, milky white, rust color, clay red, or black at the time of or after the earthquake.
Groundwater anomalies are generally explained by static strain steps or dynamic strain oscillations i.e. seismic waves. Static volumetric strain steps calculated assuming the model of Sagiya and Thatcher (1999) are extension with order of 100 nano strain, which will produce at most 50 cm of ground water level decrease for usual poroelastic materials. Although the ground water level decrease should produce decrease in flow rate, both increases and decreases in flow rate are reported in the Kumamoto-Ken Saii-shi. It is difficult to explain the anomalies solely by static strain steps and poroelastic effects. Local permeability changes caused by dynamic strain or shaking may cause some of the reported anomalies.

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Earthquakes before 6 April 1667 in southern Dalmatia and Montenegro

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Although the area of southern Dalmatia (Croatia) and coastal Montenegro is known to be prone to large earthquakes, and characterised by high seismic hazard, the actual knowledge of its pre-instrumental seismicity, as described by catalogues and published studies, is still largely imperfect. The only exception is the recently reappraised M 6.4 earthquake of 6 April 1667, Dalmatia. With the scope of getting to a revised scenario of the seismicity of the region before the large 1667 earthquake, the echo of which for sure had cast a shadow over the information on previous events, a systematic survey was performed. Historical sources for the 14th to 17th centuries were searched for, and successfully retrieved, focusing on those not yet taken into account by previous seismological studies, and complementing an earlier survey carried out more than ten years ago. Before the reinterpretation of the historical records here proposed, the earliest earthquake to appear in current catalogues was dated to 1472. This informative gap was thus partially amended with a handful of new, though unfortunately isolated, records of 14th century earthquakes, and with a critical reappraisal of a set of large and moderate earthquakes along the following 250 years. The increase in type, number, and accuracy of testimonies and earthquake records made it possible to extend more than one century backwards the availability of robust sets of macroseismic intensity data, and to assess new earthquake parameters. The newly obtained data contribute to putting into a substantially different perspective the pre-1667 seismicity of southern Dalmatia and Montenegro.

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The 1895 Ljubljana earthquake: can the intensity data points discriminate which one of the nearby faults was the causative one?

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The earthquake (Mw 6) that occurred in the central part of Slovenia on the 14th of April, 1895, affected a broad region, causing deaths, injuries and destruction. This event was much studied but not fully explained, in particular its causative source model.
The aim of this work is to contribute to the identification of the seismogenetic source of this destructive event, estimating peak ground parameters through the use of different GMPEs and computing a series of ground motion scenarios based on various fault models and nucleation points in the surroundings of Ljubljana: Vic, Zelimlje, Borovnica, Vodice, Ortnek, Misjedolski, Dobrepolje faults. The synthetic seismograms, at the basis of our computations, are calculated using the multi-modal summation technique and a kinematic approach for extended sources. In particular, we compute the maximum peak ground velocity value at 1 Hz because at high frequencies seismograms are strongly influenced by the short-wavelength complexities of the medium.
The qualitative and quantitative comparison of these simulations with the intensity field allows us to discriminate between various sources and configurations. The quantitative validation of the seismic source is done using an appropriate regression law, expressly calculated for this study. The main strong earthquakes used for this calculation are the two Bovec earthquakes (1998, 2004), the Aquila event of 2009, the two Emilia ones of 20th and 29th of May, 2012 ant the last Amatrice event of 24th of August 2016.
This study allows us to identify the most probable causative source model of this event, contributing to the improvement of the seismotectonic knowledge of this region.

*S04-2-01
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The Innsbruck earthquake of 22nd December 1689

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Knowledge of historical earthquakes has become more important in recent years. Complete and accurate information is necessary in order to carry out a coherent seismic hazard assessment of a specific area. In particular, since the introduction of Eurocode-8, the building code for the construction of earthquake-resistant buildings in Europe, the importance of new assessments of historical earthquakes due to the state of the art has increased. For seismic hazard assessment, earthquakes that occurred prior to the instrumental period must be considered. Due to the relatively long "return periods" of stronger earthquakes in Austria, the interpretation of historical earthquakes is of great importance.
The historical seismicity in Tyrol is characterized by a moderate activity and is one of the most seismic active areas of Austria.
The information on the quake of 22nd December 1689 shows that the damage in Innsbruck and Hall in Tyrol was similar to the damage resulting from the quake in 1670 (epicentre Hall, epicentral intensity=8 EMS-98). The 1689 quake caused fatalities in Hall and in Innsbruck.
The epicentral intensity was estimated with 7-8 EMS-98.
Several new sources have been found in the archives for the earthquake of 1689. A contemporary source from the city archive in Hall in Tyrol contained unknown information for this quake. The source describes the damage of the earthquake of 1689 in Hall, which leads to much more detailed knowledge of its impact on the city.
Although the event discussed occur rarely, earthquakes of such intensity can cause personal suffering and huge economic losses. It is therefore important to investigate the effects of historical earthquakes according to the state of the art.
Reports about this earthquake are known from the following cities: Augsburg, Hall in Tyrol (with St. Magdalena in Halltal), Innsbruck (Allerheiligen, Arzl, Hoetting and Muehlau) and Schwaz.

*S04-2-02
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A New Approach to Comprehend Historical Tsunami Source

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For decades, the initial wave height for a tsunami simulation has been acquired from the crustal deformation of one rectangular fault with a uniform slip in a semi-infinite media, or summation of many small rectangular faults. However, the inevitable singularity around the rectangular edge, especially near corners of a uniform slip rectangular fault is often harmful for tsunami simulations, when the source is close to the target land area. Recently, we made a new easy to use program for calculating surface deformation due to a fault of arbitrary shape with arbitrary slip distributions in a horizontal multi-layered media. We used this program for the forward modeling of some historical tsunamis in Japan, such as 1707 Hoei Earthquake, and 1611 Keicho Sanriku Earthquake. We only know rough tsunami heights for several ten points, and approximative arrival times of tsunami for some places for those historical events. However, some historical materials and paleoseismological surveys allow us to infer inundated area and its status. We show some physically plausible but rather simple models for those examples. We examined only ellipsoidal shape faults with the smoothly tapered slip amount from the center to ellipse. We also show the differences of tsunamis generated by traditional rectangular sources with uniform slip from tsunami generated by our models.
Another fatal problem frequently observed for the tsunami simulation is to confound the crustal deformation with the dynamic solution of the elastic equation, intending to include the rupture process into the tsunami calculation. Since the crustal deformation is nothing but the static solution, it only gives the final deformation after the whole source rupture movement has ceased. If the source is divided into small rectangles and the crustal deformation of each rectangle is used as the initial wave height at a certain time window, that tsunami simulation is invalid.

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Is the survival rate a clue to estimate the location of epicenter of historical earthquakes?

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1 Introduction
I took reflectively refuge during the preliminary tremors of the 2011 off the Pacific coast of Tohoku Earthquake. This experience suggested the human beings attempt to escape from house collapsing during the preliminary tremors, and duration of preliminary tremors (i.e. epicentral distance) and survival rate would have close relationship. I try to estimate the epicenter of inland earthquakes from mortality.
2 Case of the 1858 Hietsu Eq.
This earthquake occurred midnight, was double earthquake. Local governments described victims and population, number of fallen and total houses in each village. The mortality is high along the western part of the Atotsugawa fault, and nobody injured in the Shogawa valley. The ratio of fallen houses is almost homogeneous along the Atotsugawa fault and in the Shogawa valley. These facts can be interpreted that the epicenter was at the western part of the Atotsugawa fault, and later shock occurred in the Shogawa valley. The reason why is the residents in the Shogawa valley escaped from houses at the first event, thereafter the later event caused collapse of houses, and many people had enough time to escape from collapsing houses along the eastern part of the 70 km long Atotsugawa fault.
3 Case of the 1995 Hyogo-ken Nanbu Eq. This present earthquake hit a megalopolis. The mortality was closely similar distribution of the fallen buildings rate, and victims concentrated along the basin edge. The mortality has a little relationship with the epicentral distance. This fact would reflect following situations. 1) Many people could not escape from two-storied low resistant houses. 2) Many people were killed by collapsing buildings which blocked vacant grounds. 3) People have studied "Crawl under desks while shaking". The factor 2) is common in urban area in historical age. It must be cautious to make use of survival rate to be an indicator of epicentral distance for historical earthquake in urban area.

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Value of macroseismic information in earthquake studies in XX century: two case studies

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It is generally accepted that the instrumental era in seismology had started from the beginning of XX century. In most international and national projects related to earthquake cataloging two time-periods are explicitly distinguished: historical and instrumental with time-boundary at 1900. It is commonly shared opinion that instrumental determinations of earthquake parameters are much more precise and reliable. Of course, seismologists are aware that the location accuracy and magnitude assessment can be rather poor in early-instrumental period, but some problems, specific for historical earthquakes, such as duplications, do not exist. In the presentation, on the base of Altai region catalogue for 1914, it is shown that this opinion is too optimistic. Another problem is location accuracy. It is shown that there is a gross error in hypocenter location of 1978 off-shore earthquake in the Black Sea. The error is evident from macroseimic data spatial distribution. It is a serious problem because the Mw=5.7 earthquake is the largest near the Russian coast of Black Sea.

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From historical seismology to seismogenic source models, 20 years on: results and challenges

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Over the past 20 years historical seismology has gone through a silent revolution that turned it from purely descriptive to fully quantitative, transformed its outcomes from vaguely subjective to solidly reproducible, and – unbeknown to many – greatly increased its relevance far beyond the mere computation of “activity rates" in the modern SHA practice.

In Italy the main aspect of this revolution was spawned by the creation of “new generation catalogues", large databases providing for each earthquake all felt intensities along with precise identification of the reported sites and even a description of the earthquake effects. These catalogues allowed automatic processing of intensity data to derive the epicentral parameters, an equivalent magnitude and the geometric parameters of the prospective causative fault through a Fortran code termed Boxer (Gasperini et al., BSSA, 1999).

Increased data resolution and manageability allowed large Italian earthquakes sequences to be explored in depth, often revealing an unexpected source complexity and setting new constraints on the location and magnitude of the most significant shocks (e.g Fracassi & Valensise, BSSA, 2007; Burrato & Valensise, BSSA, 2008). This evidence contributed to unraveling the arrangement and behavior of large seismogenic fault systems, greatly supporting seismotectonic interpretations in areas dominated by large tectonic complexity and by blind faulting (Basili et al., Tectonophysics, 2008; Kastelic et al., MPG, 2013; Vannoli et al., Pageoph, 2015).

More recently historical data have been used to calculate earthquake budgets to be compared with geodetic evidence for ongoing strain and fault slip rates, thus strengthening earthquake recurrence models devised for seismic hazard assessment (Carafa et al., GJI, 2017).

Little of this would have been possible without historical seismology data, an often overlooked wealth of information that still awaits to be exploited in many seismogenic areas worldwide.

A STRUCTURED AND HIERARCHICAL DATABASE OF MEXICAN HISTORICAL EARTHQUAKES: 1469 TO 1912

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A structured and hierarchical database of historical earthquakes in Mexico during the last 450 years was designed and developed. The macroseismic data were located using the official Mexican almanac and to all identified locations a value of intensity on the Modified Mercalli Intensity (MMI) value was assigned. In total, 328 earthquakes were identified from 1469 to 1912. The earthquakes were classified according to their tectonic origin. The database may be queried by date, date range, seismic region or locality. Specific queries may also be made for buildings reportedly damage or associated phenomena to earthquake. The full verbatim macroseismic information may also be accessed from the database so the user can make their decision regarding the interpretation. When sufficient data were available, the epicenter and magnitude of the earthquakes was estimated following the inversion method of macroseismic data points proposed by Bakun and Wentworth (1997). For this purpose, attenuation curves of attenuation versus moment magnitude were constructed for three general categories of earthquakes in Mexico: subduction zone, in-slab earthquakes in the subducted Cocos plate and crustal earthquakes. As a first example, the resulting catalog has been used to study the seismicity of the Trans Mexican Volcanic Belt (TMVB). This region is where the largest concentration of the population of Mexico lives. As a result, several crustal earthquakes on the TMVB were identified, which were previously unknown. The database is open and available to any interested user at http://sismoshistoricos.org/.

Dynamic Rupture Modeling of Historic, Pre-Instrumental Earthquakes on the San Andreas and San Jacinto Faults, Southern California

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Southern California has an active record of instrumentally-recorded earthquakes, but its pre-instrumental historic record of damaging earthquakes is also extensive. Paleoseismic studies, and analysis of firsthand descriptions of ground motion and damage have attributed some of these events to specific fault sections. However, with the density of active faults in southern California, many of these interpretations are non-unique. Dynamic rupture modeling can be a helpful tool for further interpretation of these observational datasets. This type of modeling allows for physics-based assessment of plausible rupture paths and processes within complex fault systems. The models can take observation-based fault geometry, stresses, and surrounding geological setting as site-specific initial conditions; the calculated slip and ground motion patterns can then be compared to historic and paleoseismic records to determine the best match. Here, I discuss how I have used dynamic modeling to examine, and in some cases reevaluate, several historic earthquakes traditionally associated with the San Andreas and San Jacinto faults in inland southern California. A similar approach would likely also be helpful in examining source faults and processes in other regions with long historic pre-instrumental earthquake records.

*S04-3-03
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THE 7TH JULY, 1923, CANAL DE BERDUN EARTHQUAKE, IN THE PYRENEES. ITS MACROSEISMIC FIELD FROM CONTEMPORARY RECORDS

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Seismicity rate in the Pyrenees can be considered moderate. Nevertheless, damaging earthquakes occurs as it is well known from their historical seismicity records. Among them, the 7th July, 1923, known as Canal de Berdun earthquake, is one of the biggest events (maybe the largest one) occurred during the instrumental period in this region. As it occurred in a sector with low population density, and the produced damage was, consequently, moderate, not much attention has been paid to it.

Its size, recently re-estimated from waveform inversion of contemporary seismograms, on the order of Mw 5.4, and unique location among the large earthquakes in the Pyrenees, in the central, south part of the chain, make this event of great interest for a better definition of the regional seismicity. For this reason we decided to study a new its source from the analysis of the available contemporary macroseismic records and related documents.

Observatory Fabra, in Barcelona, preserves a large collection of macroseismic records of earthquakes occurred in the North and East of Spain during the XX Century. Among them, the whole documentation of the survey on occasion of the 7th July 1923 earthquake in the Pyrenees. A detailed reanalysis of these records, complemented with information published in the contemporary press and studies allowed a reconstruction of the macroseismic field in the Spanish side of the Pyrenees. From it macroseismic estimates of the epicentral location and magnitude, in very good agreement with the instrumental ones, are obtained. We present the different steps of the undertaken research, some of the obtained results and its consequences for the regional seismicity and we compare them with present earthquakes occurred in the same region.

*S04-3-04
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The newly discovered 1885 earthquake in the French Guiana - Brazil border, 6.0 mb, the largest historical mid-plate event in South America.

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On August 4, 1885, a strong tremor was felt along 1400 km of the Amazon river, from Belem near the coast to Urucurituba near Manaus, with intensities reaching IV-V MM, as reported by all newspapers of Belem and Monte Alegre, Parah state. The French Seismic catalogue (http://www.sisfrance.net/Antilles/) reports a strong shaking (intensities V to VI MM) in Cayenne and Guisanbourgh, French Guiana. Other, independent accounts of this earthquake were reported by newspapers in Surinam (V in Paramaribo) and Guyana (IV in Georgetown). A survey of all available macroseismic data indicates the event was felt up to 1200km distance. We used an intensity = f (magnitude, distance) attenuation relation for Brazilian intraplate earthquakes to locate the best epicenter and magnitude of the 1885 earthquake. The epicenter was located in the border between French Guyana and Brazil and a magnitude of 6.0 (+- 0.3) mb was estimated. This event is one of the largest to have occurred in mid-plate South America. Previously known large events in northern Brazil were 1955.01.31 in Mato Grosso state (6.2 mb) with an average felt radius of about 600 km, and the 1985.08.03 Amazonas (5.5 mb) felt up to 420 km, on average. Other historical accounts of earthquakes felt near the border between French Guiana and Brazil (1949, ~5.3 mb; 1951, ~4.8 mb) as well as the recent 2006, 5.2 mb, event near Caienne, suggest that this region could be regarded as a seismic zone, not previously considered in seismotectonic studies in South America.

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An intensity database for earthquakes on the Highveld of South Africa from 1840 to 1950

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A database of macroseismic observations from historical earthquakes on the Highveld of South Africa was compiled as a contribution to the seismic microzonation of Johannesburg and the Witwatersrand Basin. The database contains over 3,000 intensity data points (IDPs) that have been assigned from macroseismic observations retrieved from questionnaires, newspaper reports, Observatory log books, Government reports and published seismic compilations. The database includes IDPs from 199 tectonic earthquakes felt in and around Johannesburg between 1840 and 1950. IDPs from over 700 mining-related earth tremors between 1907 and 1950 are also included. Seventeen tectonic events and 28 mining-related tremors have 10 or more IDPs each. Both datasets are comprised of relatively low intensity values mostly determined from human perception of shaking, largely indoors, rather than structural damage. However, 102 and 76 of IDPs from each dataset respectively have intensity values of V MMI-56 or higher. The occasional strong earthquake is consistent with the tectonic setting of the Highveld. The moderate magnitude mining related tremors are shown to increase in frequency, intensity and magnitude as the gold mines progress deeper. This database represents a thorough review of all the available sources of information and correction of transposed digits and other errors in previous compilations. This review also reveals the benefits of using additional contemporary resources from different languages, governments and disciplines in the compilation of IDP datasets. The database led to the development of a seismic history for the Highveld and the gold mines, considering the broader geo-political context of the rise of the independent Boer republics, the “mineral revolution" and the establishment of Johannesburg, and the course of colonial rule in southern Africa.

*S04-4-01
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Methodology to Determine the Parameters of Historical Earthquakes in China

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China is one of the countries with longest culture history. Meanwhile China has been suffered very heavy earthquake disaster, so abundant earthquake recordings remained. In this paper, we try to outline some basic information about China historical sources of earthquakes and the achievements of research. There were two large-scale collections of historical earthquake archives in China. We also introduce China intensity scale and the editions of historical earthquake catalogues. Total four formal editions of “The Catalogue of Chinese Earthquake" were compiled. Spatial-temporal and magnitude distribution of historical earthquake are analyzed briefly. The practice procedures of tradition methods were illustrated. Generally, the parameters of an historical earthquake were determined according to the relation between the parameters and intensity data. Several such relations were listed which often used in China. Owing to rely heavily on the historical earthquake archives, the traditional method has its limitation.

Besides traditional methods, we also illustrate a new approach to amend the parameters of historical earthquakes or even identify candidate zones for large historical or palaeo-seismic earthquakes. In the new method, a relationship between instrumental recorded small earthquakes and strong historical earthquakes is built up. Geophysics implication of new method was analyzed. The modern-day seismicity can point out the locations of persistent weaknesses in the lithosphere. Such persistent has also been observed on a much smaller scale in the location of acoustic emissions (AE) during cyclic loading in laboratory rock deformation tests. From view of fracture mechanics, the occurrence of a strong earthquake means that the local crust medium has been experienced a process of changing. The new method might help us to judge historical earthquake parameters and amend them, even find a new candidate site.

*S04-4-02
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Document database for historical earthquakes around Tokyo area

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The Tokyo metropolitan area has suffered many damaging earthquakes, since the beginning of shogunate capital in Edo (former name of Tokyo) in 1603. During the Edo period (1603-1867), the 1703 Genroku Kanto earthquake and the 1855 Ansei Edo earthquake caused the severest damage; the casualties were estimated as 10,000 for each event. The 1703 earthquake is considered to be an M˜8 plate-boundary earthquake, similar to the 1923 Kanto earthquake which caused the worst disaster in Japan, and the damage was documented in wide area. The 1855 earthquake (M˜7) seems to have occurred just beneath Tokyo, because the damage was mostly limited in Edo city.
We constructed the full-text digital document database for these earthquakes, as well as other smaller earthquakes that caused damage in Edo and suburbs. For the 1703 earthquake, the total number of records is 378, including memorial monuments of tsunami victims in Boso peninsula. For the 1855 earthquake, numerous documents including caricature were published, and only a part of them has been included in the database. The database contains about 1200 records from other 35 earthquakes in and around Tokyo area in the Edo period. For about a half of them, historians emended the descriptions and assigned the reliability of documents.
The database has similar format as the Online Database of Historical Documents in Japanese Earthquakes and Eruptions in the Ancient and Medieval Ages (Ishibashi, 2009) which covers the earthquakes between 416 and 1607 with about 3000 records.

Estimation of source regions of large earthquakes from felt reports of JMA seismic intensity database - Evaluation of applicability to historical large earthquakes -

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Can felt reports of historical documents be used to estimate the source of large earthquakes? Before establishing a new methodology, we show that the source area of recent three large earthquakes (2004 Niigata-Ken Chuetsu, 2008 Iwate-Miyagi, and 2011 Fukushima-Hamadori earthquakes) can be imaged from the spatial distribution of felt reports by using the JMA seismic intensity database. Our preliminary results imply the possibility that the large earthquake source can be constrained from spatial and temporal distribution of felt reports.
For the case of the 2004 and 2008 earthquakes, number of aftershocks with felt reports decreases with increasing distances at epicentral distance <100 km from the mainshock, while they fluctuate at epicentral distance >100 km, probably due to site condition and/or attenuation structure. This indicates that the effects of site amplification near surface and heterogeneous attenuation structure should be properly taken into consideration in a new methodology to estimate source of historical earthquakes. For the case of the 2011 earthquake, the number of aftershocks with felt reports fluctuated even within 100 km from the mainshock, because of the aftershocks following the 2011 Tohoku-oki earthquake.
Source of a historical large earthquake has been traditionally estimated from distribution of or casualties recorded in historical literature. However, the damage was caused by not only a ground shaking but also tsunami, massive fire and/or landslide. In addition, the distribution of building damage is strongly controlled by the population density and elapsed years since constructed. In some historical literature, earthquakes that were felt without any damage are also reported as well as damage description from major earthquakes, whereas these were not fully utilized except for several previous studies (e.g., Matsui and Oike, 1997; Satake, 2002; Matsu'ura and Tsuji, 2010).

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Historical Earthquake of Georgia

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This work discusses the historical earthquakes that occurred in Georgia during the period between 1250 BC and 1900, and the problems associated with their study. Many monuments of cultural heritage and architectural buildings have the signs of seismic effects. Despite the wide range of analytical work done in compiling historical earthquake catalogues some arguable interpretation of the data on certain historical earthquakes, inaccuracies in determining the parameters were still preserved in these fundamental studies. In addition, significant information existent in numerous original sources has remained undeveloped. They can provide important data for the quantitative parameterization for the newly discovered historical earthquakes Georgia. It is noteworthy that only a little quantity of geologic, geomorphologic and archaeological data was used for the parameterization of historical earthquakes in Georgia in each of the above mentioned catalogues. Methodology for creating a catalogue of historical earthquakes is based on transformation of descriptive data of damage in terms of macroseismic intensity range, as well as on determination of its location, magnitude, focal depth and their errors. This parameterized catalogue represents the full database of historical earthquakes that affect the territory of Georgia. The summarized map of the distribution of maximum damage in the historical period (before 1900) on the territory of Georgia clearly shows the main features of the seismic field during this period. In particular, in the axial part and the southern slope of the Greater Caucasus there is a seismic gap, which was filled in 1991 by the strongest earthquake and its aftershocks in Racha. In addition, it is also obvious that very high seismic activity in the central and eastern parts of the Javakheti highland is not described in historical materials and this fact requires further searches of various kinds of sources that contain data about historical earthquakes.

*S04-4-05
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S04. Historical and macroseismic studies of earthquakes

How to Cope with Earthquakes in Himalaya?

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Earthquakes are one of the worst natural calamities. The Himalayan seismic belt extending from Kashmir to Arunachal Pradesh has been seismically one of the most active intra-continental regions. The Gorkha earthquake of Mw 7.8 on April 25, 2015 broke a long seismic quiescence in the central Himalayan region. Many studies indicate that enough strains have accumulated to generate Mw 8 and larger earthquakes in the region. It is also argued that the Gorkha earthquake may not have released the accumulated strains and larger earthquake(s) should occur sooner or later. As short time earthquake forecast is not possible (though there are some success in medium term forecasts), and earthquake shall continue to occur. We need to develop earthquake resilient society. Developing earthquake scenarios as what would happen if one of the earlier earthquakes repeats today, and sharing it with the concerned state governments and public is extremely helpful. A couple of very successful exercises were conducted by the National Disaster Management Authority, Government of India, for a repeat of the 1905 Kangra earthquake and the 1897 Shillong earthquake during the years 2013 and 2014. The 1905 Kangra earthquake had claimed ~ 19,000 human lives. For a hypothetical earthquake of Mw 8, occurring near Mandi in Himachal Pradesh, a scenario was developed taking into account the estimated intensities, population density, typology of the houses. It was inferred that the human lives lost would be several folds higher than ~19,000 lost during the 1905 Kangra earthquake. Detailed preparations were undertaken before the mock drill conducted on the 13th February 2013 involving the states of Punjab, Haryana, Himachal Pradesh and the Union Territory of Chandigarh. A similar exercise was conducted for the eight north-east Indian states for the repeat of the Shillong earthquake of 1897 during 2014. Several short- comings in preparedness were identified. The best part was public awareness generation.

*S04-P-01
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Development of historical earthquake and volcanic activity database using historical diaries

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Japan is exposed to frequent disaster risks of earthquakes and volcanic eruptions. Descriptions on these natural disasters can be found in a large amount of historical diaries that were written by officials of local governments before the middle of AD 19C. These historical diaries were often used as official records of local governments and contain descriptions about natural phenomena such as daily weather, earthquake ground shaking or volcanic smoke. Since these descriptions were made on the same day as those phenomena occurred, they are highly credible. Furthermore, the place where the diaries were written can be precisely specified. Since the same person kept the diary for several decades, continuous and stable information can be obtained. In Kinki district, especially around the ancient capitals, Kyoto and Nara, the historical diaries have been existed from the ancient and medieval (AD 10-16C) eras providing the continuous records of about 900 years. From the modern times (AD 17-19C), the historical diaries can be found nationwide. Therefore, it is possible to analyze seismic and volcanic activities of the historical era by utilizing the historical diaries before observations of modern instruments began.
In this research, we analyze the historical diaries and extract the high-quality records of natural phenomena such as sensible earthquakes and volcanic smoke to create a database. In addition, we will create a geographic information system based on this database to show spatio-temporal distributions of felt earthquakes and volcanic activities of the historical era. By combining the present analysis with earthquake and volcanic researches based on modern instrument observations, we aim to elucidate the long-term nationwide earthquake and volcanic activities in Japan from the historical era to the present day.

*S04-P-02
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Source area and magnitude of an aftershock following the 1854 Ansei-Nankai earthquake

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Great earthquakes repeatedly occur along the Nankai trough, where the Philippine Sea plate is subducting beneath the Eurasian (or Amurian) plate. The 1854 Ansei sequence have two great earthquakes: the eastern part (Tokai region) ruptured first and the western part (Nankai region) ruptured about 32 hours later. Historical documents show that the Ansei Nankai earthquake associated several aftershocks with strong shakings. The source region and magnitude of the aftershocks have been inferred from the descriptions of historical documents, but an exception is an aftershock that occurred on the New Year's eve on a Japanese classical calendar, which strongly shook Kochi, close to the plate boundary. In this study, we try to quantitatively estimate the magnitude and source region of this aftershock. Firstly, we inferred the seismic intensity from historical documents. The historical documents show that the ground motions were prolonged and suggest that the ground motions were rich in long-period components. Next, we estimate the source region and magnitude from the seismic intensity data, evaluating the residuals between the observed (interpreted) seismic intensities and the calculated ones with the aid of the Bayesian statistics. The seismic intensities were calculated with an empirical attenuation relationship, in which a finite fault was assumed. It is highly probable that the magnitude was larger than seven, and we found that the source region would be located to the southeast from Kochi. However, the inferred source location is not consistent with the historical descriptions that the number of felt earthquakes around Kochi greatly increased after this event, which suggests that seismicity increased around the region. Our inferred location is not closely located to Kochi. This inconsistency might be responsible for the effect of rupture directivity, which is not taken into consideration in the attenuation relationship used in this study.

*S04-P-03
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What age distributions of stone lanterns tell about historical earthquakes?: case studies at three sites in Japan

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Strong ground motion often topples stone lanterns, small stone objects standing in precincts of Japanese temples and shrines, which are observed in recent large earthquakes in Japan. Topple of stone lanterns occurs when the ground shaking is equal to or larger than JMA Intensity 5, which is roughly equivalent to MM Intensity 7. Descriptions of similar damage are found in historical documents, and have been used to estimate seismic intensities of historic ground motion. Design and size of old stone lanterns are similar to those of modern ones, which makes them practical sensors of ground motion at least for last 500 years. It is a customary practice to engrave the date of dedication in the stone lantern and we can identify stone lanterns which have experienced major historical earthquakes. This means stone lanterns as a group are records of historical earthquakes and in this study we explore what we can learn from such non-textual materials. Increase/decrease of stone lanterns frequently occur by anthropogenic or religious reasons, and quality of data is essential in identifying effects of earthquakes. We surveyed stone lanterns at three sites: Kitano-Tanmangu Shrine, Kyoto, Iwashimizu-Hachimangu Shrine, Yawata, and Zenkoji Temple, Nagano. These three sites are known for historical large earthquakes and a large numbers of stone lanterns in their small precincts. We are able to identify that historical earthquakes has weak effects on age distributions of stone lanterns. Among our findings are that very large earthquakes apparently wiped out stone lanterns in early years, and that dedication of stone lanterns apparently increases a few years after the earthquake, an indication of recovery from the disaster. It is difficult to estimate severity of historical ground shaking from stone lanterns.

*S04-P-04
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S04. Historical and macroseismic studies of earthquakes

The Japan GIS Database of the Historical Disaster using research data of Archeological excavation, Geological survey and Historical documents.

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Nara National Research Institute for Cultural Properties has started this project since 2014, supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under its Earthquake and Volcano Hazards Observation and Research Program. The purpose of this project are to 1) collect all historical evidence of natural disaster in Japan based on research data of archaeological excavation, geological survey, and historical documents, 2) build a GIS database that can make easily to study, simulate, and develop several disaster mitigation systems, programs, and methods, and 3) open to the public for area studies of hazards. In this session, I would like to present a new result of this GIS model.

*S04-P-05
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Numerical reconstruction of the source rupture and strong ground motions of the 1935 Hsinchu-Taichung Earthquake, Taiwan from historical triangulation data

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On 21 April 1935, a large earthquake with a local magnitude of 7.1 struck central Taiwan, named the Hsinchu-Taichung earthquake. It was the most destructive earthquakes in Taiwan history since 1600. This event was associated with two major faults: the northern one as the Shihtan reverse fault, and the southern one as the Tuntzuchiao right-lateral strike-slip fault. To understand its possible rupture history of the associated faults, and its potential impact to Taiwan of a destructive earthquake of this kind, we reconstructed the possible source characteristics and the strong ground motions of the 1935 Hsinchu-Taichung earthquake using historical triangulation data as the reference. There are three main types of fault model for this event, as two previously proposed fault models and a combined model. We investigated the spatial slip distribution based on these models from source inversion by using the triangulation data that is in the time of 1917-1937. In comparison to about 60 stations of the triangulation data, we chose a best model for a scenario for ground motion simulation by Spectral-Element Method (SEM). The preferred (best fit) inversion result suggested that this earthquake was composed of four fault-segments, as two observed surface rupture faults to the north by reverse faulting and to the south by strike-slip motion, and with two blind faults without surface rupture in between. We also compared the spatial slip distribution, the synthetic ShakeMap, and the historical intensity distribution for various scenarios to examine the possible hazard from the reconstructed source model. Results from this study suggested that the multiple fault-segments might rupture from adjacent fault segments with different styles of faulting.

*S04-P-06
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The large Hyuga-nada earthquake on June 30th, 1498 is a fake earthquake –Examination of the damage descriptions in Kyushu in the war chronicle "Kyusyu-gunki"–

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A large earthquake in Hyuga-nada Sea on the east side of Kyushu Island, Japan along Nankai Trough in "Mi-no-koku" (9-11 a.m.) on June 30th, 1498 on Julian calender, which was based on the descriptions about serious damage due to a large earthquake in Kyushu in the war chronicle "Kyushu-gunki", has been accepted by many seismologists as the 1498 Meio Hyuga-nada earthquake. "Kyushu-gunki" is one of the popular novels which was written more than 100 years after the 1498 event. The damage descriptions have been used to estimate the location of this earthquake without evaluating the reliability. In this study, in order to assess credibility of the description, we carefully examined writing process of "Kyushu-gunki" and damage descriptions in this war chronicle. Our findings are summarized as follows: (1) "Kyushu-gunki" was completed in Kyushu in 1607, hence the writers' experience of the contemporary 1596 destructive earthquake in Kyushu might have influenced the description of the damage of 1498 earthquake; (2) Damage descriptions of "Kyushu-gunki" were generic without location information and most of them are cited from descriptions of damage in Kyoto due to the 1185 large earthquake in the war chronicle "Gempei-josui-ki"; (3) Origin time ("Mi-no-koku") of this event is described only in "Kyushu-gunki" and it is close to that of the 1498 great Tokai earthquake ("Tatsu-no-koku": 7-9 a.m.); (4) The chapter of the earthquake damage also includes serious famine in Kyushu in 1503 and pains of people by many disasters, making this chapter a stage setting for later stories. To make a story of the war chronicle more interesting, writers seem to have created fictitious story of serious damage due to a large earthquake in Kyushu based on old war chronicles and some records of the 1498 Tokai earthquake. Therefore, it can be concluded that the 1498 Meio Hyuga-naga earthquake is a fake earthquake and it should be deleted from Japanese historical earthquake catalog.

*S04-P-07
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S04. Historical and macroseismic studies of earthquakes

Revisiting source parameters of the 1906 Meishan, Taiwan earthquake from full-waveform measurements of historical records

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The 1906 Meishan earthquake (M7.1) was one of the largest damaging earthquakes in Taiwan in the early 20th century. Historical literatures and recent studies showed that the Meishan earthquake was related to the Meishan Fault and had a right-lateral faulting mechanism striking in east-west direction. With the historical Omori records at station Taipei, Taichung and Tainan, we carried out a waveform simulation of the 1906 Meishan earthquake for understanding source rupture properties of the 1906 Meishan earthquake and the yielding predicting ground-motion in the region. A two-step waveform simulation based on SGT (strain Green's tensor) is carried out for this attempt. In the first step, possible fault models of the 1906 Meishan earthquake from geological survey and recent studies are compiled for simulation. As the preliminary results, with an east-west strike faulting mechanism as Meishan fault, the synthetic waveforms and intensity maps were not well explained. We, thus, further carried out a grid-search in focal mechanism by fitting first-motion and shear-wave polarities of historical records and synthetics to evaluate possible focal mechanism. By comparing the simulated intensity distribution maps with the historical records, the Meishan earthquake is suggested to be associated with a north-south striking thrust faulting mechanism. Also by comparing the converted waveforms from the 1999 Chiayi earthquake to the Gray-Milne seismograms recorded at the ancient station Penghu and Tainan, the similarity of the waveforms also convinces that the Meishan earthquake might have a similar focal mechanism of a north-south striking thrust fault with the 1999 Chiayi earthquake. According to our results and the distribution of the aftershocks, the surface rupture of the Meishan fault might be a transfer fault between two thrust faulting systems in the western coastal plain of Taiwan.

*S05-1-01
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S05. Preservation and usage of analog seismogram archives

On guidelines for preservation and usage of analog seismogram archives

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Seismology is an observational science, and seismograms routinely exhibit features that are not yet fully understood.

The time-scale of earthquake occurrence requires examination of ground motions recorded over periods far longer than the three decades now available from the era of digital recording. Most underground nuclear test explosions, and almost all atmospheric nuclear tests, took place during the era of analog recording.

Different countries have taken different approaches to making analog seismograms usable in the modern era. There is much to be learned from shared experience. Can we develop consensus on those analog records that must be rescued, and preserved with metadata, for use by future generations? We can hope to learn from advanced programs of data rescue, applying successful methods to unexplored archives.

About fifteen different United States institutions hold substantial archives of analog seismograms, containing information needed by future generations of researchers. Consensus is needed on selection of datasets that should be converted from analog to digital form, for use by younger generations who often expect data centers to provide digital data from well-characterized instruments. Such selection of suitable datasets, can be informed by circulating practical information on the level of effort needed—information that has been acquired by countries that have engaged in this type of work for decades.

The Lamont Geological Observatory of Columbia University deployed a sparse global network of Press-Ewing instruments in the mid-1950s, preceding the WWSSN deployment by several years. I give examples of analog recordings of large atmospheric explosions that exhibit phenomena not recorded via digital media---including, from the 1950s: high-altitude explosions above the Pacific recorded teleseismically; and multi-megaton explosions in the atmosphere recorded on vertical component seismometers via the effect of density variations in the air.

*S05-1-02
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Twenty-five years of activity of the ESC Working groups devoted to the preservation of the tangible and intangible heritage of Euro-Mediterranean seismology

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At the beginning of 1990 the Istituto Nazionale di Geofisica started promoting the TROMOS project devoted to the research, recovery, restoration and enhancement of the historical heritage of seismology in Italy. The project was not confined to strictly seismological disciplines, embracing as the history of science, scientific instruments and technology.
In 1992, with the establishment of the ESC WG "History of seismometry" (HoS) the experience of Tromos was extended to the whole European area. The activity of the WG has increased the awareness of the importance of the tangible heritage of instrumental seismology (seismograms, bulletins, manuscripts, etc); as a consequence, in 1997 a first census of Euro-Mediterranean historical seismic stations and the relevant instruments, was published.
As an evolution of the HoS, in 2002 a new ESC WG "History and data of instrumental seismology" (HDIS) was established, and a collaborative project EuroSeismos was launched in the WG's framework.
The experience and the technologies of SISMOS of INGV in Rome have allowed to broaden the "user base" of the project to the whole Euro-Mediterranean area. During the period 2003-2010 around 30,000 historical seismograms from 34 Euro-Mediterranean countries have been scanned at Sismos and now are freely shared online to the whole seismological community (seismogramrequest.rm.ingv.it).
Finally, at the ESC General Assembly in Moscow on 2012 a new ESC WG "Methods and data for the study of earthquakes recorded on pre-WWSSN historical seismograms" took the place of HDIS. The aim of this WG is to investigate earthquakes in the Euro-Mediterranean area, using seismograms of the pre-WWSSN era and other data.
During 25 years, the activity of these ESC WGs involved tens of members, produced tens of papers and more then hundred of presentations in seismological and history of science meetings enhancing the scientific and cultural value of the tangible and intangible heritage of Euro-Med seismology.

The contribution of the Sismos project to the preservation, dissemination and scientific usage of the material heritage of instrumental seismology of Euro-Mediterranean area

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In view of the long Italian tradition in instrumental earthquake observation, on 2001 INGV officially started the Sismos project for the research, recovery, high resolution scanning and dissemination of seismograms recorded in Italian and Euro-Mediterranean area observatories during the period 1895 -1984 (sismos.rm.ingv.it/en/). The Sismos High resolution scanning laboratory is equipped with 3 flat bed A0 format scanners, and the seismograms are scanned at 1016 dpi grey scale.
A major effort was made to intervene in the different sectors (scientific, historical, cultural and popular dissemination) with the disciplinary rigour of the different disciplines and synergies involved as compared with analogous initiatives at the national and the international level.
During the period 2006-2010 SISMOS was part of the facilities of the European project NERIES, from 2010 and 2012 participated to the GEM project, and is also a seismological infrastructure (History and data of instrumental seismology) of the European Plate Observing System (EPOS).
SISMOS pays also particular attention to the recovery, restoration and conservation of historical materials relating to Italian and international seismology with scientific as well as cultural aims.
Since 2008, two restoration laboratories have been set up at Sismos, one for historical papers (i.e. seismograms, bulletins, etc.) and one for historical instruments.
Since 2005, SISMOS has developed a specific software for the viewing and processing of raster images of historical seismograms into a vectoral form: Teseo2 - Vectorizer of historical seismograms (teseo.rm.ingv.it/). The program has been extensively used by SISMOS researchers and foreign colleagues.
A new database and a new interface of the SISMOS portal make more efficient the request and download of some of the over 200,000 seismograms' raster images (seismogramrequest.rm.ingv.it) and relevant instrument's constants (over 20,000) and station bulletins (over 500,000 pp).

*S05-1-04
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation /
S05. Preservation and usage of analog seismogram archives

A brief introduction to the analog seismograms storage in China

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From 1950 to 1980, China Earthquake Administration(CEA) finished the construction of National Seismic Network with 86 stations, among them 24 stations equipped with short period seismograph, broad band seismograph and long period seismograph, and 62 stations equipped with short period seismograph. From 1996, supported by the central government and local governments, CEA launched national projects of updating the seismological observation facilities into digital seismological observation systems. By the end of 2007, CEA had accomplished analog to digital conversion of the then existing seismological observation systems and set up 1007 digital seismic stations. This indicates full digitization of seismological observation in China.
From 1950 to 2007, CEA accumulated a huge mass of analog seismograms, some seismographs are stored in Institute of Geophysics, and some seismographs are stored in provincial seismological earthquake administration. Due to storage in different regions, some seismograms have been damaged or lost. We must sort through these valuable historical seismograms and input to computer timely for proper record.
CEA pay more attention to analog seismograph rescure, we scanned about 40,000 seismographs with 600 dpi in jpg format in 2015. With the helps of Prof. Paul Richards and Dr. Won-Young Kim, we installed the analog seismograph digital software SeisDig and digitized some seismographs in 2016. SeisDig is a Graphical User Interface (GUI) based interactive digitizing tool, digitizing operations are mouse selected.

*S05-1-05
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Analog Seismogram Archives at Earthquake Research Institute, the University of Tokyo

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Earthquake Research Institute of the University of Tokyo has several kinds of archives of analog seismograms and mareograms. First one is Historical Seismogram Collection, which includes seismograms recorded at Tokyo (at various locations and instruments around Hongo with a total of 213,579 records from 1887 to 1986), Tsukuba (10,769 records for 1922-1962), and Wakayama (12.650 records for 1922-1968). Seismograms at particular locations and dates can be searched at the website: http://wwweic.eri.u-tokyo.ac.jp/susu/en/. The oldest record from large earthquake is from the 1891 Nobi earthquake recorded at Hongo on a circular paper. Teleseismic data includes the Hongo record on the Omori seismograph, the world's first continuous seismograph, from the 1899 Alaskan earthquake. While they are archived as microfilms by 1990's, the resolutions were poor for some records and users need to go back to the original records. Second one is collection of foreign seismograms. Old seismograms between 1899 and 1917 at Taiwanese stations can be searched at http://wwweic.eri.u-tokyo.ac.jp/record-W/taiwan_kisyo-e.html. Microfilms of Canadian Seismograph Network between 1981 and 1989 are archived. For WWSSN stations, Almost complete microfilm data (~100 stations) from 1963 to 1988 are available. The coverage can be seen at http://wwweic.eri.u-tokyo.ac.jp/wwssn/filmlist.html (only in Japanese). The last one is tsunami waveform data http://wwweic.eri.u-tokyo.ac.jp/tsunamidb/index.html (only in Japanese). Tsunami waveforms recorded on Japanese tide gauges from large earthquakes between 1911 and 1996 are scanned and archived. Guest uses can see the list (sorted dates, earthquakes or locations) of 3097 records, but registration is required to download the images.

*S05-1-06
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The current status of archives of the old analog seismograms in Japan, and some examples of their preliminary contribution to seismology

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Since 2004, we have been cooperating to make digital image archives of old analog seismograms preserved in the following institutes:
National Astronomical Observatory of Japan, Mizusawa (records of Latitude Observatory), Tohoku University (records of Mukaiyama Observatory, and Yagiyama Seismological Observatory), and Kyoto University (Kamigamo Observatory, Abuyama Observatory, and Aso Volcanological Observatory) are mainly for smoked paper-seismograms.
Hokkaido University (Urakawa Seismological Observatory, Sapporo Center, and some temporal stations), and Earthquake Research Institute, the University of Tokyo (Tsukuba Observatory, and Dodaira Observatory) are mainly for 35mm film-seismograms and ink-recorded seismograms recorded after 1960's.
We also made the digital image archive of world seismograms on 1933 Showa Sanriku Earthquake, which were collected by the late Prof. Takeo Matsuzawa soon after the event. Although most archives are still under construction, here we would like to show our current achievement and some examples of their primitive usage.
Although we have the very good earthquake catalogue in Japan for the period from 1885, there still remain some earthquakes of questionable hypocenters and magnitudes for old events. 1911 off the Kikaijima Island earthquake of M8.0 is one of these events. It was felt even in Osaka, separated nearly 900 km from the epicenter. Gutenberg (1954) assigned 160km depth to this event. However, tsunami damage was reported in some nearby islands. When we could compare a seismogram recorded in Mizusawa of 1911 event with that of the 1901 shallow event of M7.0, whose epicenter is very close to the 1911's, it is really easy to conclude that the both events are shallow. It was confirmed by some seismograms preserved in abroad, too. We will report some other examples of the power of digital image archives of old analog records.
We appreciate the late Prof. Motoya, and many persons who have involved in the archiving operations.

*S05-2-01
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S05. Preservation and usage of analog seismogram archives

Historical seismograms: Preservation efforts for an endangered species

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The long recurrence times characteristic of major earthquakes (typically one to several centuries) result in severe undersampling of the Earth's seismicity as documented by digital seismic networks (at most 40 years old), or even their immediate predecessor, the WWSSN (55 years old). For this reason, historical seismograms (typically from 1900 to 1962) are absolutely crucial to the understanding of seismic cycles, notably at major subduction zones.
Yet, these precious datasets are often perceived by administrative stakeholders as antiquated, obsolete and of little value, and are thus threatened with disposal and irreversible destruction. This situation is aggravated by the aging and eventual disappearance of the older generations of seismologists who were trained in the techniques allowing the modern processing of such records.
We present a review of typical analog datasets of historical seismograms and of the techniques available for their preservation through transfer to digital supports.
We focus on the Northwestern University Seismogram Archive Facility, which presently holds an estimated 5 million seismograms on photographic support, including a rich WWSSN collection, and complete archives of the Pasadena/Southern California network for 1923-1962, as well as significant holdings of records from the former Soviet Union, Japan, and other critical stations.

*S05-2-02
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Modern methods applied to historical seismograms: Perspective and examples

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The long recurrence times characteristic of major earthquakes (typically one to several centuries) result in severe undersampling of the Earth's seismicity as documented by digital seismic networks (at most 40 years old), or even their immediate predecessor, the WWSSN (55 years old).
Yet, crucial information can be extracted using variations of modern techniques routinely applied to digital data.
We present a review of these algorithms, notably the PDFM moment tensor inversion and the application of energy- moment discriminants. We will review several examples, including the resolution of the "twin eights" of 17 August 1906, the quantification of the slowness parameters of the 1932 Manzanillo, 1947 Hikurangi and 1934 Santa Cruz tsunami earthquakes, and focal mechanism solutions for two major plate boundary events, on 01 May 1915 in the Kuril Islands and 26 June 1941 in the Andaman Islands, which are both shown to be incompatible with a shallow-angle thrust geometry. Application to large normal faulting intraplate earthquakes (e.g., Sanriku, 02 March 1933) is particularly important given the probably longer recurrence times of such events, which are thus even more undersampled by modern records.

*S05-2-03
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Instrumental polarities of the most important historical seismographs of the Euro-Mediterranean area

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One of the many critical issues in the use of historical seismograms is the knowledge of the polarity of the seismographs with mechanical and galvanometric recording system.
This information is not easy to find and rarely appears in the seismological literature or seismic bulletins. Periodical collection, on a global scale, of this and other information of instrumental parameters is not always reliable or it do not refer to the same definition of polarity.
The considerable efforts to use scientifically historical instrumental records (i.e. pre-WWSSN), to calculate for example the focal mechanism are often made vain due to the uncertain reliability of information on the polarity of the historical instruments.
For the most popular historical instruments that have operated in the Euro-Mediterranean during the period 1910 – 1980 we determined the instrumental polarity comparing those expected for a set of 10 earthquakes of known mechanism with those read on over 700 seismograms.

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PRESERVING ANALOGUE SEISMOGRAMS OF REGIONAL NETWORKS AND OTHER DOCUMENTS. EXPERIENCE AT THE INSTITUT CARTOGRAFIC I GEOLOGIC DE CATALUNYA (ICGC)

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Catalonia, in the NE of the Iberian Peninsula, has a long tradition on seismic recording. First seismic station in this regions, EBR, still active, was installed in 1904. The second one, FBR, started in 1906 and it is also active. Both keep their seismograms and a large amount of complementary information. Since then several initiatives succeeded.

One of them is the Catalan seismic network. Started in 1985, it can be classified as regional network. As it was quite common at the time, short period vertical sensors were used. Most of the seismograms obtained up to year 2000 were recorded on thermal paper support. At ICGC we keep at present around 28000 record sheets from the period 1985-2000. Such kind of support is unstable and records become whitened after few years. Thus, even we are dealing with post WWSSN era records, actions to preserve them are needed urgently and the posed problems and needs are similar to those of the WWSSN and earlier records.

To save these records for the future, a campaign to scan them as images has been undertaken. These seismograms show some specific features when compared with WWSSN or older records (ex. The high frequency content of the signal obliges to use high density scanning -1200 dpi). As this successful experience can be useful to preserve records of other regional networks, we present here the adopted strategies for scanning, classification and diffusion and some preliminary results from their analysis.

These projects joint other initiatives developed at ICGC for preserving and diffusion of other materials as seismic bulletins, macroseismic records, etc. of the older stations EBR and FBR. Some examples will be also presented.

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Observations of large earthquakes in the Mexican subduction zone over 110 years

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Fault slip during an earthquake is observed to be highly heterogeneous, with areas of large slip interspersed with areas of smaller or even no slip. The cause of the heterogeneity is debated. One hypothesis is that the parts of the rupture surface that have large slip during earthquakes are coupled more strongly, whereas the areas in between creep continuously or episodically, partially releasing strain energy during the interseismic period. This would lead to subsequent earthquakes having large slip in the same place, or persistent asperities. A second hypothesis is that in the absence of creeping sections, the prestress is governed mainly by the accumulative stress change associated with previous earthquakes. Assuming homogeneous frictional properties on the fault, a larger prestress results in larger slip, i.e. the next earthquake may have large slip where there was little or no slip in the previous earthquake, which translates to non-persistent asperities.

The study of earthquake cycles are hampered by short time period for which high quality, broadband seismological records, needed for detailed studies of slip distributions, are available. The earthquake cycle in the Mexican subduction zone is relatively short, with about 30 years between large events in many places. We are therefore entering a period for which we have good records for two subsequent events occurring in the same segment of the subduction zone.

In this study we compare seismograms recorded either at the Wiechert seismograph or on a modern broadband seismometer located in Uppsala, Sweden for earthquakes in the Mexican subduction zone rupturing the same patch. The Wiechert seismograph is unique in the sense that it recorded continuously for more than 80 years, without changes in the instrument response. In total we have registers from more than 20, M>6.9 earthquakes in seven along trench segments.

Our observations indicate that some asperities are persistent over time, whereas others are not.

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ANALYSIS OF THE ANALOG SEISMOGRAMS RECORDED DURING THE NOVEMBER 19, 1912 (M˜7.0) ACAMBAY, CENTRAL MEXICO EARTHQUAKE: TOWARDS A FINITE SOURCE INVERSION

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The Acambay earthquake of November 19, 1912, was an M˜7.0 shallow intraplate rupture that broke a large portion of the Acambay-Tixmadeje Fault System in central Mexico. The earthquake produced extensive damage in several towns close to the fault and was strongly felt in Mexico City. This event generated a 40.0-km-long surface rupture trace, with a peak observed dislocation of ˜0.5m. To date this is one of the most important continental earthquakes occurred in Mexico. During 1912 six seismographic stations were operating in Mexico with different Wiechert and Bosch-Omori mechanical seismographs. An extraordinarily detailed report shows it was recorded by most of horizontal and vertical instruments at the six stations. Up to 2016, only 11 from the original 22 smoked-paper seismograms, from five of the stations that recorded the earthquake were found to be recovered.

In this work using standard and ad-hoc methodologies we obtained the digital, evenly-sampled time series for the ground motion velocities for each of the available seismograms. To do this, we first carried out a high resolution scanning of the original traces. Then, due to the condition of the seismograms we manually digitized them, following the seismic trace in ascending time. Therefore we corrected the distortions of seismic traces for their pen curvature, uneven paper speed, skews, and non-zero baselines following the Grabrovec and Allegretti (1994) procedure, and additional ad-hoc corrections were made using linear approximations when abrupt changes in traces occurred. After this, we resampled the unevenly digitized traces to a constant-time interval to 100 samples per second using a spline interpolation method. Finally we performed an instrument correction procedure to obtain the actual ground velocities for each instrument and component. Once corrected, the unclipped portions of seismic data were used to perform a linear finite-source inversion for the slip distribution on the fault surface.

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Database of digitized data of analog seismic and tsunami records for historical earthquakes in Japan

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Seismic and tsunami instrumental observations by seismographs and tide gauges in Japan started in 1875, and a huge number of analog records of earthquakes and tsunamis are stored at various universities and institutes in Japan. Re-analysis of historical records based on modern waveform analysis methods, high-performance computers and current knowledge on the velocity structure would produce new results and interpretations of the mechanisms of earthquakes and tsunamis that can improve hazard mitigation practice. However, it requires extensive time and skills to digitize the analog waveforms recorded on paper. We are currently constructing the database of digitized historical records for major earthquakes in Japan, for example, the 1923 Kanto, 1944 Tonankai, and 1946 Nankai earthquakes, with the cooperation of many institutes such as universities, government agencies, and companies. In this presentation, we introduce the prototype of the database. The data can be searched by event name, station name, and seismograph name. Users can obtain the instrumental constants if they are available, in addition to the digital data. We target to open this database in a few years via National Museum of Nature and Science and Earthquake Research Institute of the University of Tokyo. Contribution of digitized waveforms are welcome from any seismologists in the world. The database on the museum website will play an important role for outreach of seismology.

*S05-P-02
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HERP data retrieval system of JMA analog seismograms

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Since 2006, we have scanned selected analog seismograms observed at about 150 stations deployed by Japan Meteorological Agency (JMA), and constructed a database of the scanned digital images.
Digital image of each seismogram is obtained by scanning the entire seismogram at once using a large flatbed color scanner with a 400 dpi resolution, and saved as a TIFF-format file. Due to the depth of focus, we can get clear seamless images even for not-flat seismograms. As of January 2017, we obtained more than 138,000 image files of seismograms recorded at 100 stations, by various types of seismographs, such as Gray-Milne-Ewing type seismograph (G.M.E), Wiechert Seismograph, and mechanical strong motion seismographs. In those data, there are many precious records of the destructive earthquakes like the 1891 Nobi earthquake.
The images of seismograms for 91 stations can be now available through the web site:
http://www.susu.adep.or.jp/
The images for the rest stations are under processing to be added to the database.
In the database, the seismograms can be searched by date, station name, and components. The size of one original TIFF-format image file is around 200 MB, then all images are highly compressed as JPEG2000 files for easy preview and download.
Constants of static magnification, natural period and other parameters of the used seismographs are also collected.
The database has begun to be utilized for research, such as re-investigation of the 1914 earthquake at Kagoshima (Ogata et al., 2016). We are planning that the web site will become one of the Wiki page, in which data of the seismograms digitized by researchers are open after getting their permission.
Acknowledgement
This project has been supported by the Headquarters for Earthquake Research Promotion (HERP) of the Ministry of Education, Culture, Sports, Science, and Technology in Japan. We thank to Dr. Masayuki Okuno, Mr. Yukio Hirai, Mr. Atsushi Kamata, and Mrs. Yoshiko Suzuki.

*S05-P-03
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A trial application of analog seismograms of the Kanto-Tokai observation network for crustal observation to the detection of deep low frequency tremor

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Continuous digital seismic data from dense seismographs network lead to the discovery of deep low frequency tremor (hereinafter, tremor; Obara, 2002). In this study, we examined whether the analog recordings are useful to reveal past activities of tremor in the Tokai region, central Japan. National Research Institute for Earth Science and Disaster Resilience (NIED) operated the Kanto-Tokai observation network for crustal observation since 1979 (hereinafter, Kanto-Tokai network; Okada et al., 2000). While this data was mainly used to locate hypocenters of earthquakes around the Kanto and Tokai region in Japan, continuous seismic data in the vertical component has been stored as analog seismograms on recording paper. In the early 2000's, the seismographs of the Kanto-Tokai network were taken over to Hi-net and fully digitized.
The seismograms of the Kanto-Tokai network were recorded by pen recorders. Two-hours recordings are divided into four blocks in a sheet. Upper and lower blocks are the odd and even hours, respectively. Blocks in the left and right columns show seismograms from 0 s to 35 s, and from 30 s to next 5 s (i.e. 65 s) for each minute, respectively. Each block contains 60 traces. Small and large time ticks are marked every second and every minute, respectively.
We checked the analog recording around the period in which SSEs are detected by a tiltmeter since 1984 (Kobayashi et al., 2006). Actually, signals dominant in several Hz with the amplitude of several hundreds of nm/s are found at some stations in the Tokai region. This is characteristic to tremor, while time difference between recognized tremor and the SSE catalog is sometimes about two days. This may be attributed to the spatial migration speed of tremor and SSE (typically 10-20 km/day), as the tiltmeter station is about 20 km south from the closest seismograph. In addition, we found possible tremor from Oct. 29 to Nov. 2 in 1980, before the period analyzed in Kobayashi et al. (2006).

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Source parameters of the 1952 Pyeongyang, North Korea, earthquake

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There was a rather large felt earthquake on March 19, 1952 from Nampo City, west of Pyeongyang, the capital of North Korea. The North Korea Seismological Institute estimated the magnitude of the event around 6.5 (Seismological Institute of North Korea, 1987). They might estimate the magnitude from traditional method, i.e. felt area survey since there was no seismic station in the Korean Peninsula at that time. Furthermore it was during the Korean War. Considering the low to moderate seismicity around the Korean Peninsula, the 1952 North Korean event is exceptional and may be the largest event since the 20th century. For this event, we collected eight seismogram copies from Japan, China, and Russia. However many seismograms show very weak traces. We could digitize rather good quality data only from three stations, Abuyama and Matsushiro in Japan and Sverdlovsk in Russia. To determine the earthquake source parameters, we applied moment tensor grid searching method and compare the observed and synthetic seismograms for the above three station data. We found the best fitting with strike 120 degrees, dip 90 degrees, rake 340 degrees, and seismic moment 2.45*10^25 dyne-cm, which is relevant with moment magnitude (Mw) 6.17.

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STUDY OF THE 7TH JULY, 1923, CANAL DE BERDUN EARTHQUAKE, IN THE PYRENEES FROM CONTEMPORARY SEISMOGRAMS AND BULLETINS

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Seismicity rate in the Pyrenees can be considered moderate. Nevertheless, damaging earthquakes occurs in this region as it is well known from their historical seismicity records. Among them, the 7th July, 1923, known as Canal de Berdun earthquake, is probably the largest one, according to the moment magnitude Mw = 5.4 that we compute in this study. Its size and unique location among the large earthquakes in the Pyrenees, in the central, south part of the chain, make this event of great interest for a better definition of the regional seismicity. For this reason we decided to study its source from the analysis of the available contemporary seismograms and related documents.

After a throughout collection and selection, 20 records for this earthquake have been digitized and processed. They were obtained at 9 different European stations. The event has been relocated and its magnitudes recalculated. We further characterized the earthquake through time domain moment tensor inversion. We obtain appropriate fits to regional recordings filtered in an intermediate period band (20 s to 50 s) for a pure normal faulting source with strike parallel to the Pyrenees (N292E), dip of 66 degreesand rake angle of -88 degress. The best fitting depth is 8 km. While previous normal faulting events in the Pyrenees occurred close to the axial zone and the highest topographies, suggesting a relation of seismicity to postcollisional extension, the location of this important normal faulting event at the southern frontal thrust of the Pyrenees suggests that this interpretation may be too simplistic.

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ROMANIAN NETWORK OF ANALOG SEISMOGRAMS: CONTRIBUTION TO IMPROVE GLOBAL EARTHQUAKE CATALOGS

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Romania has a long tradition in recording and investigating seismic events. The first historical instrumental recordings are available starting with 1902. Since then, the number of analog stations has continuously increased reaching in 50' a number of 7 observatories equipped with different seismographs with recordings on black paper, photo paper and ink paper. After the major earthquake of 4 March 1977, benefiting from UNDP-UNESCO assistance, the national network was improved with a telemetric network of 15 seismic stations with data recorded on paper.
Over time, Romania analogue network provided and exchanged seismic data (bulletins, seismograms, reports) with international agencies (International Seismological Summary, International Seismological Centre, National Earthquake Information Center, National Earthquake Information Service) and participated with a significant number of analog seismograms recorded at strong earthquakes in Europe to the international projects EUROSEISMOS, SISMOS and NERIES. Recently, in addition to the classic archive of analogue recordings, a modern digital database has been created in the National Institute for Earth Physics (http://archive.infp.ro/). Until now, over 200000 seismograms have been scanned. With the new digitization and vectorization software which is now available, the source parameters can be reconsidered.

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Trends in ground-based nuclear explosion monitoring research and development

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There have been significant technological and scientific revolutions in the fields of seismology, acoustics, and radionuclide sciences with regard to the Comprehensive Nuclear-Test-Ban Treaty (CTBT), which opened for signature in 1996. It is valuable to pause now and observe the arcs of progress evident in the body of research results reported in the literature related to improving monitoring capabilities. To this end, authors from several national laboratories have prepared a report entitled “Trends in Ground-Based Nuclear Explosion Monitoring Research & Development – A Physics Perspective". The document reviews the accessible literature for four research areas: source physics (understanding signal generation), signal propagation (accounting for signal changes with distance), sensors (recording the signals), and signal analysis (processing the signal). It addresses over 40 trends, such as moving from 1D to 3D earth models, from pick-based methods to full waveform methods, and from separate analysis of sensor data to integrated analysis. Highlighted in the document for each trend are the value and benefit to the monitoring mission, key papers that advanced the science, and promising research and development for the future.

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The ISC datasets for monitoring research

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The International Seismological Centre (ISC) is a non-governmental organization based in UK and funded by 69 research and operational institutions in 45 countries. The main mission is to produce the global definitive Bulletin of earthquakes and other seismic events based on reports from over 130 seismic networks worldwide. The ISC Bulletin is the most long-term and comprehensive source covering the period from 1904 to 2017.

Soon after seismic event occurrence, the ISC collects preliminary bulletin reports from various seismic networks and agencies around the world. Once integrated together, they form a bulletin of very recent global seismicity. These preliminary reports are later substituted, one by one, with fully reviewed reports from the same agencies and form the basis for the comprehensive and reviewed ISC Bulletin. Thus, at any time with respect to each seismic event occurrence, the ISC Bulletin remains a great reference source of information for various studies of monitoring product's completeness, quality and calibration.

In addition, the ISC maintains and distributes several derivative datasets that are used in monitoring research: the ISC-EHB bulletin - a groomed subset of the ISC Bulletin containing well-recorded teleseismic events; the IASPEI Reference Event List (GT) – a bulletin of events for which the hypocentral information is known with high confidence (to 10km or better); the ISC Event Bibliography - an interactive facility that enables searches for references to scientific articles devoted to specific natural and anthropogenic seismic events that occurred within a region and time period of interest.

Here we describe major advances recently made by the ISC to extend and improve these datasets that are openly available and widely used in monitoring research. These datasets are also used by the ISC as a basis of its interactive service “The CTBTO Link to the ISC database" used by the personnel of many National Data Centres.

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Synthetic seismograms of explosive sources calculated by the Earth Simulator

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We calculate broadband synthetic seismograms using the spectral-element method (Komatitsch & Tromp, 2001) for Jan. 6 2016 DPRK event (Mw(USGS) 5.1). We use Earth Simulator system in JAMSTEC to compute synthetic seismograms using the spectral-element method. The simulations are performed on 8,100 processors, which require 2,025 nodes of the Earth Simulator. We use one chunk with the angular distance 40 degrees to compute synthetic seismograms. On this number of nodes, a simulation of 10 minutes of wave propagation accurate at periods of 3.0 seconds and longer requires about 2 hours of CPU time. We use CMT solution of Rozhkov et al (2016) as a source model for this event. This source model has 43% CLVD component, 19% double couple component and 38% isotropic component. The hypocenter depth of this solution is 1.4 km but we put the hypocenter at the surface for this computation. Comparisons of the synthetic waveforms with the observation show that the arrival time of Pn and Pg waves matches well with the observation The surface waves observed are also modeled well in the synthetics, which shows that the CMT solution we have used for this computation correctly grasps the source characteristics of this event.

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Model ensembles for estimation of seismic travel time and event location uncertainty

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We explore the use of model ensembles to characterize the uncertainty of seismic travel time predictions. Our emphasis is on 3D earth models and we include a standard, radially symmetric (1D) models for comparison. Traditional parameterization of travel time prediction uncertainty – as a function of event-station distance – provides a representative global average, but uncertainty characterization can be unrepresentative when errors throughout a large geographic region deviate significantly from the average. Recent efforts to characterize path-specific travel time uncertainty have made great strides, but ad hoc multiplication factors must be applied to uncertainty estimates for them to be reconciled with observed error. The mismatch between estimated uncertainty and observed error is likely due to epistemic errors, for which model-error covariance is typically unknown. The model ensemble approach leverages the efforts of many research groups that have rendered images of earth structure. To the extent that researchers use differing data sets, model parameterization, methods of travel-time prediction, or imaging, predictions based on an ensemble of models will improve robustness of travel time uncertainty. In our initial effort, we use a set of seismic models to compute P-wave travel times for a global set of events with well-characterized location uncertainty. Agreement and divergence of travel time predictions for each model globally, regionally, and for each path are examined to study the variability of model predictions. The test events are relocated and epicenter uncertainties are estimated using each model and using estimates of uncertainty based on an ensemble calculation. The consistency of location errors and uncertainties are used to assess the model ensemble approach. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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On similarities and differences of signals measured by IMS stations from five DPRK underground tests

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Seismic, hydro-acoustic, and infrasound stations of the International Monitoring System detected seismoacoustic signals from five declared underground tests conducted by the DPRK. These data allow thorough quantitative comparison aimed at understanding of the similarities and differences in seismo-acoustic wave generation by underground explosions. In routine automatic and interactive processing, the International Data Center found all five events, fused seismo-acoustic, estimated absolute locations and magnitudes together with their uncertainties. The International Seismological Centre makes these results available for the broader monitoring community. In this study, we extend the estimates of relative characteristics of detected signals to station level using standard methods adapted at the International Data Centre (IDC). In addition, we apply several techniques based on waveforms cross correlation (WCC), which are under development at the IDC. The WCC method allows significant improvement in the accuracy of relative location, magnitude, and seismic moment tensor estimation.

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Source array analysis for accurate relative event location at the North Korea nuclear test site

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Between October 2006 and September 2016, 5 declared underground nuclear explosions carried out at the Punggye-ri test-site in North Korea were detected both at regional and teleseismic distances. Double-difference relative location estimates are quite network-sensitive with inter-event distance estimates from regional Pn phases consistently longer than estimates from teleseismic P-phases. The seismic wavefield leaving the test-site is more complicated than predicted by a 1D velocity model. Slowness corrections for each of the rays leaving the source region can be found which reduce the double-difference time residuals and provide relative location estimates which are consistent for all seismic measurements. Source-array analysis provides a different approach to modelling the seismic wavefield leaving the DPRK test-site and supports the hypothesis that the slownesses for regional Pn waves are frequently underestimated. Given the number of events now recorded at the test-site, source-array analysis provides an important tool for analyzing subsequent events which may be problematic for classical double-difference methods. One such scenario is a low magnitude event recorded only regionally, with limitations in azimuthal coverage. Another is a test in a different part of the site for which the waveform similarity is significantly diminished at some stations.

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Seismic wave analysis of North Korean nuclear tests using seismographic networks in Japan

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Seismic waves generated by a series of North Korean nuclear tests in the past decade have been observed in seismic networks deployed throughout the Japanese Islands. Seismic signals corresponding to Pn arrivals are observed clearly at seismic stations of Hi-net (High Sensitivity Seismograph Network) and F-net (Broadband Seismograph Network) deployed by NIED (National Research Institute for Earth Science and Disaster Resilience).

We analyzed the waveforms of the five nuclear tests recorded at Hi-net and F-net stations. Apparent path-average velocities of Pn waves and their maximum amplitudes are estimated from observed seismograms in the vertical component. We found significant regional variations of apparent path-average velocity and maximum amplitude along propagation paths, which are likely to reflect the structural variations in the crust and uppermost mantle beneath the Sea of Japan. For example, fast apparent Pn velocity and larger amplitude are observed in the paths across the Japan Basin in the northern part of the Sea of Japan, which is characterized by thinner curst (about 9 km), while slow velocity as well as relatively smaller amplitude are found in the paths to Kyushu, which traverse the eastern margin of the Korean Peninsula with thicker crust.

Such regional variability of Pn wave speeds and amplitudes makes it difficult to precisely estimate the source parameters and yield of explosion, by using only the Japanese seismographic network without any proper correction for 3-D structure in the curst and uppermost mantle beneath the Sea of Japan. Such Pn wave anomalies derived from the past explosions observed throughout Japan may be of help in empirical corrections for the rapid and precise determination of hypocenter and yield of explosive source.

*S06-P-02
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Long-range underwater acoustic propagation from controlled underwater sources received at IMS hydroacoustic stations

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Controlled impulsive scientific underwater sound sources in the Northwestern Pacific used for lithosphere studies, and observed at two IMS hydroacoustic stations in the Pacific Ocean were studied. Although the energy released from these sources is significantly smaller than that of nuclear explosions, the signals were recorded by ocean bottom seismometers and IMS hydroacoustic stations thousands of kilometers away from the source. These experiments provide calibrated yield, time and locations for long-range acoustic transmissions, which enable the examination of the physics of long-range acoustic propagation. The IMS stations employed in this study were HA03 (Juan Fernandez Island) off the coast of Chile in the Southeastern Pacific, and HA11 (Wake Island, USA) in the western Pacific. Both stations have two triplets of hydrophones located in the SOFAR channel and monitor the oceans for signs of nuclear explosions. HA03 detected sources that were located above flat terrain at distances of 15,000 km across the Pacific and above the landward slope off the coast of Japan at distances of 16,000 km across the Pacific. These records demonstrated that bubble pulse characteristics in the signal could be preserved over the long propagation distances.

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The CTBTO Link to the ISC Database

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The "link to the International Seismological Centre (ISC) database" is a database visualisation web interface, specifically designed and implemented to fulfil the needs of the monitoring community. It provides both PTS and National Data Centres with dedicated access to seismological datasets maintained by ISC, notably, the ISC/ISS bulletins of natural seismicity of the Earth, mining induced events as well as nuclear and chemical explosions; the ISC-EHB bulletin and the IASPEI Reference Event list (GT). Special access to the datasets is provided by four basic categories: the Area based spatio-temporal search (based on ISC Bulletin), the REB based spatio-temporal search (based on specific REB events), the GT event based search and the IMS station based search (historical reporting patterns of stations close to IMS sites). Via the dedicated searches the user can submit queries to the ISC database, create various maps and plots, download the data, carry out comparisons of the parametric data, and relocate REB and GT events on the fly. The ISC is committed to maintain and further develop the link's capabilities as it is extensively used by the NDCs and PTS and is proved to be a useful tool during both the NDC Preparedness Exercise and the OSI Integrated Field Exercise.

*S06-P-04
IASPEI Symposium / IASPEI01. Seismological Observation and Interpretation / S06. Advancement in methodologies for CTBT monitoring

Similarities and differences of a hydrogeological response to underground nuclear explosions and earthquakes

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We analyzed hydrogeodynamic state change due to large-scale underground nuclear explosions that had took place on the Semipalatinsk testing area (USSR, present Kazakhstan) in 1983-1989. We performed to mark out several key stages of hydrogeodynamic state change:
1. Excess pressure camber forming at the moment of the explosion
2. Drop-like or gradual level decrease to the initial value or even below depending to entire volume of induced fracturing and existence of hydraulic link to zones that were weakened by explosion and connected to explosion epicenter.
3. Establishment of quasi-stationary underground water flow and subsequent level recovery to the initial static state.
Marked stages' duration depends on explosion characteristics, geological-structural and hydrogeological conditions of testing area. We discovered that both co-seismic and post-seismic hydrogeological effects due to explosions are often similar to those associated with the passage of the waves of large-scale earthquakes in the case of solid massif but can differ in the affected zones of faults of different range. We considered vertical velocity of ground motion as the parameter of comparison.
We found out differences in the nearest zone of explosions and earthquakes in case of peak ground velocity exceeding 40 cm/s. Maximum water level decrease lasted more than three months after the burst in the wellbore on the Semipalatinsk testing area whereas post-seismic level changes after earthquakes usually end in hours or days. Certain exceptions tend to fault zones where water level alterations sometime come up to tens of meters. Following research will show does this difference relates either to local geological-structural peculiarities of different fault zones or inherent physics of impact.

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*S07-1-01
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S07. Strong ground motions and Earthquake hazard and risk

Source parameters, path attenuation, and site effects from strong-motion recordings of the Wenchuan aftershocks (2008-2013) using nonparametric generalized inversion technique

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S-wave amplitude spectra from 928 strong-motion recordings, which were obtained at 43 permanent and temporary strong-motion stations in 132 Ms 3.2-6.5 earthquakes occurred in the vicinity of the fault plane of the 2008 Wenchuan earthquake from May 12, 2008 to December 31, 2013, are collected for determining the source spectra, path attenuation, and site responses using a nonparametric generalized inversion technique (GIT). Some source parameters are determined by the grid-searching method. Seismic moment (M0) and corner frequency (fc) vary from 2.0*10^21 to 1.7*10^25 dyne*cm and from 0.1 to 3.1 Hz, respectively. Stress drop mainly ranges from 0.1 to 1.0 MPa, significantly lower than the globally averaged level. S-wave energy-to-moment ratio is approximately 1.32*10^-12. The source scaling properties are studied by analyzing these parameters. It shows that the moment magnitude (Mw) is universally lower than the surface-wave magnitude (Ms) or local magnitude (ML) measured by China Earthquake Network Center (CENC). M0 is proportional to fc^-3, and stress drop has no significant dependence on the size of earthquake, which implies self-similarity for earthquakes in this study. It shows that larger stress drop of aftershocks generates at the areas where smaller slip occurs in the main shock. The inverted path attenuations show that geometrical spreading in region of the Wenchuan earthquake sequence is weak and significantly depends on the frequency. The frequency-dependent S-wave quality factor (Qs) is regressed to be 143.9f^0.97 at frequencies from 0.5 to 20 Hz. The inverted site responses are compared with those given by the previous study (Ren et al. 2013), showing that both studies provide compatible results for most of stations. The site responses are obviously different at different stations of a terrain array, higher at the hilltop and lower at the hill foot, which indicates ground motion is significantly affected by the local topography.

*S07-1-02
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Estimation of Source, Path and Site Effects in Hangay region Mongolia using a dense broadband seismic array

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We applied a spectral inversion method to data from a broadband seismic array in Hangay region, Mongolia to estimate source, local site and propagation path effects. The 72-stations database comprises a total of 1331 waveforms from 32 earthquakes (3.0 < Ml < 5.6). To secure the accuracy of hypocenter locations, first we relocated hypocenters using the detected P-wave arrival times. The averaged P and S-wave velocities estimated from the relocated hypocenters are 6.1 km/s and 3.5 km/s, which corresponds well to those of upper crust model (CRUST 2.0). We also obtained seismic moment and focal mechanism of each earthquake based on the time-domain moment tensor inversion and P-wave polarities. The results show that strike-slip faults are dominant in the target region and estimated magnitudes range from Mw 2.9 to Mw 4.5. In the spectral inversion method, we applied two kinds of approaches, which use reference site and reference events in the inverse problem for computational stability. We found that two different inversion approaches gave similar results in the frequencies range between 0.5 and 10 Hz. The predominant frequencies at each site correspond well to those from horizontal-to-vertical (H/V) spectral ratios of S-wave portion. Finally we estimated seismic moment, corner frequency and static stress drop for each event using our inversion results. Our results indicate that a large amount of dataset from the dense seismic network provides fundamental and useful information for seismic hazard assessment in this region.

*S07-1-03
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground M
otion / S07. Strong ground motions and Earthquake hazard and risk

Estimation of site amplification using ground motion records at strong motion stations in Turkey

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A strong ground motion network has been operated in whole of Turkey by AFAD (Prime Ministry Disaster and Emergency Management Authority, Turkey). Strong motion records from the observation have provided important data in understanding strong motion features and reasons of damage in many past earthquakes in Turkey. Many studies on local site effects in many areas in the country have been conducted using strong motion records, such as Avcilar area in the west Of Istanbul (Ozel et al., 2002).
In this study we have estimated site effects at the AFAD stations in whole of Turkey. Strong ground motion data observed during 754 earthquakes at 465 strong motion stations were used to estimate effects of source, propagation path and site amplifications using a spectral separation technique in the frequency domain at a frequency range of 0.5 to 20Hz. Since we used theoretical amplification of soil layers over the basement with an S-wave velocity of about 2km/s as similar to Ozmen et al. (2016), the estimated amplification factors in our analysis can be regarded as effects of all geological layers over the basement. Q-values are slightly larger than those from previous studies. Most of the source spectra can be explained with the omega-square model. The amplifications at most of the sites in the central part of Turkey are small at all the frequency, while large amplification factors are found at sites in the south-western part of Turkey and along the east Anatolian fault. In particular the amplification factors are large at high frequency at some stations around the Marmara sea suggesting effects of shallow soil. We furthermore discuss relationships of the amplification factors with averaged S-wave velocity values in some depths at some of the stations.

*S07-1-04
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground M
otion / S07. Strong ground motions and Earthquake hazard and risk

Preparation of 1D velocity structure using records from moderate sized earthquakes

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Kathmandu Valley is a tectonic basin filled with thick (~600 m) fluvio-lacustrine sediments. It carries a history of many damaging earthquakes occurring in and around Nepal Himalaya; 2015 Gorkha Earthquake being the latest one. Its thick unconsolidated sediment and location in seismically active region has made a large population vulnerable to earthquakes. An understanding of underground structure is necessary for mitigating the earthquake damage. We've used earthquake records from four strong motion seismometers to estimate the 1D velocity structure of the valley. Moreover, records from six additional temporary seismic stations are also used for the purpose. This is a step towards preparation of 3D basin structure of the valley. We considered the records from station KTP, installed over rock site, as input motion and simulated the observed waveform of sediment sites by Propagator Matrix Method. The initial velocity model for the simulation was prepared by consultation of available borehole logs, geological map, and geological cross-sections of the Kathmandu Valley. We fixed the average velocity and density of the geological layers based on previous studies. The models were then adjusted to fit the simulated and observed waveform of a moderate earthquake (mb4.9) occurred in 2013 August 30. We then checked the adjusted models with two Mw5.1 aftershocks of the Gorkha Earthquake with encouraging agreement between observed and simulated waveform. We also used the Diffused Field Theory Method to cross-check the 1D velocity models. Since, the temporary sites were installed after the Gorkha Earthquake, we tried adjusting the velocity models using the DFT method and checking them with Propagator Matrix Method for another moderate sized (mb5.5) earthquake resulting in good agreement. The adjusted velocity models show bedrock depth at 150-480 m indicating an uneven basin topography of the valley.

*S07-1-05
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Regional Difference of Ground Motion for Shallow Crustal Earthquake in Taiwan and California

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While performing the probability seismic hazard analysis, one most important question is if the ground motion model developed for one region can be used directly to another region. In order to answer this question, we should confirm if there is a significant difference of ground motion between two regions at first stage, identify the origin of the difference in second stage, and quantify the difference for different ground motion scenario in third stage. Generally, it can be evaluated by different approaches including (1) comparison of available ground motion models; (2) analysis of variance for ground motion database; (3) verification of ground motion model relative to regional data; (4) development of ground motion model with basic function form for two regions. In this study we discuss the regional difference of ground motion for shallow crustal earthquake in Taiwan and California as a case study by developing the ground motion model with basic function form for two regions. We compare the spectral shape, magnitude scaling, depth scaling, distance scaling, style of faulting factors, linear and nonlinear site effects for two regions to identify the origins of the difference. The ground motion difference is quantified by evaluating the ground motion ratio between two regions for different ground motion scenario. This ground motion ratio can be used to adjust other ground motion model from one region to another region for the probability seismic hazard analysis.

*S07-2-02
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground M
otion / S07. Strong ground motions and Earthquake hazard and risk

Determination of Design Spectra with considering different site classification, in Andisheh suburb of Bandar Abbas, South of Iran

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A design spectrum is based on a statistical analysis of a collection of numerous spectra of different recorded ground motions in different earthquakes, with possible modifications based on engineering experience. By application of design spectra in seismic analyses, determination of design spectra for different site conditions improved the accuracy of seismic analysis results. Since Bandar Abbas is located in a high relative hazard zone (0.3 g) and the soil is soft in this region, also the city is in the presence of water, probability of liquefaction is high when the earthquake occurs. In this study we used 15 accelerograms with considering four characters such as: magnitude, epicentral distance, focal mechanism and site effect conditions for calculating hazard assessment. Seismosignal, EERA and Seisrisk 3 softwares were used to process data. Based on boreholes data and seismic profiles, the shear wave velocity model was obtained. Finally the design spectra parameters and microzonation maps were produced and presented to structural designers.
Keywords: Bandar Abbas, Design spectra, ground motion, seismic analysis, shear wave velocity, Microzonation, Hazard assessment

*S07-2-03
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Joint project on seismic hazards in the Indo-Gangetic Plain, India: Results from Ground Motion Sensor network

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An Indo-Japanese "SATREPS-DISANET" project was jointly implemented by the Earthquake Research Institute, Tokyo and National Geophysical Research Institute, Hyderabad, India during 2010-15 in which a network of 26 Strong Motion Velocity meters was established in the Indo-Gangetic plains (IGP) to assess seismic hazard in the region. The Himalaya represent a continent-continent collision boundary and is the locale of four M>8.0 earthquakes in the past. The project was taken up to map shallow subsurface structure of the sediment filled fore land basin and to study seismic wave amplification to assess seismic hazard in the region and to develop ground motion prediction equations.

The network became operational from October 2012 and recorded two significant earthquakes, viz., the 2014 Bay of Bengal earthquake (Mw 6.1) and the 2015 Gorkha earthquake (Mw 7.9), as well as the larger aftershocks. The analyses of the data provide a glimpse of seismic-wave amplification in the IGP on a regional scale. During the 2014 Bay of Bengal earthquake, the PGA and PGV values in the IGP were up to 3 and 4 times the corresponding values on the adjacent hard sites, respectively. The observed SSRs in the IGP estimated from the data of the relatively deeper 2014 earthquake (depth between 60 and 80 km) recorded at far distances (975 ⊠ Δ ⊠ 1650 km) are found to be reasonably similar to those from the shallow Gorkha earthquake at closer distances (350 ⊠ Δ ⊠ 680 km). Details of sediments thickness estimation and shear wave velocity in the IGP highlighting the implication of seismic risk in the region are presented. A passing remark on the outreach activities undertaken under the joint project will be made.

*S07-2-04
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S07. Strong ground motions and Earthquake hazard and risk

Seismic Hazard Assessment of the 1995 Kobe Earthquake: Before and After

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The 1995 Kobe earthquake was a turning point for the seismic hazard assessment in Japan. Since then, the Headquarter of Earthquake Research Promotion has been established at the government. Crustal and subduction earthquake potentials are evaluated, and the national seismic hazard map was released in 2005. The ground motion prediction technique for broadband time histories is validated for recent crustal earthquakes (e.g., 2000 Tottori and 2005 Fukuoka) and past subduction earthquakes (e.g, 1944 Tonankai, 1946 Nankai, 1968 Hyuga-nada, 1978 Miyagi-oki, and 2003 Tokachi-oki). However, there are no validation of crustal earthquakes before the 1995 Kobe earthquake. From this motivation, we estimate ground motions for the 1995 Kobe earthquake using the prediction technique and information before and after the earthquake. The first approach is based on the ground motion prediction equation (GMPE). Fukushima and Tanaka (1990) is used as the pre-Kobe GMPE with site amplification factors released before 1995. As for the post-Kobe GMPE, Si and Midorikawa (1999) is used with latest site amplification factors. The comparison is performed at each mesh following the procedure of Ishikawa et al. (2011). The second approach is based on the empirical Green's function method with source modeling. We compare a homogeneous source model that follows the scaling laws of Matsuda (1975) and Takemura (1998) as the pre-Kobe source model, and a characterized source model from Kamae and Irikura (1998) and the recipe of Irikura and Miyake (2001, 2011) as the post-Kobe source model. In addition to the above fault models, various source models are recently proposed by kinematic, pseudo-dynamic, and dynamic approaches. Since the comparison technique is valid for these approaches at each period, it is useful to judge ground motion pulses that enhance response spectra.

*S07-2-05
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Recent Seismicity and Potential Earthquake Risk in Major Ethiopian Cities

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The East African Rift is one of the most classic examples of active continental rifts that we witness to date. Active tectonics manifests itself through moderate magnitude seismicity and volcanism in the region. Major cities and towns in Ethiopia are located either within the active rift floor or the nearby margins where small farming villages got highly urbanized over the years which is unintended overlap that exacerbated earthquake risk in the area.
The January 24, 2016 earthquake of magnitude 4.4 Mw occurred nearby the highly populated Awasa town at 18:34:32 UTC which was widely felt all over the town with minor damage on buildings. The Awasa University students panicked from high rise student dormitories and minor injuries were reported. Another earthquake of magnitude 4.6 Ml occurred on December 4, 2016 at 01:56:15 UTC at the rift margin 40 km south of Ankober town and about 90 km NNE of Addis Ababa. It was widely felt in Addis Ababa where a number of residents from different part of the city reported their feeling to the media. On January 27, 2017 an earthquake of magnitude 5.3 Mw ruptured at 16:29:23 UTC, 160 km south of Addis Ababa just on the eastern side of Lake Langano. This earthquake was widely felt in most of rift valley towns in Ethiopia as far as Addis Ababa and it has been a subject of discussion both in the public and mainstream media in the country.
Addis Ababa being one of the fastest growing cities in sub-Saharan Africa and as the capital of Africa, there is a threat due to potential earthquake risk which has never got due attention by the concerned. The Ethiopian Seismic Station Network (ESSN) is beaming real-time data, though limited by frequent power failure and poor internet connectivity, and monitoring earthquake and volcanic activity in the Horn of Africa region. However, awareness in the society and all the concerned is still low which demands a coordinated effort in the years ahead so as to mitigate possible earthquake risk.

*S07-3-01
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S07. Strong ground motions and Earthquake hazard and risk

Reconciliation of Canada's 5th Generation Seismic Hazard Model results with those from the OpenQuake-engine

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The Geological Survey of Canada (GSC) has contributed earthquake hazard information for the National Building Code of Canada (NBCC) since the 1953 edition. The 2015 national hazard model update included many important advances on its predecessors, including: probabilistic treatment of the Cascadia subduction zone; reconfigured seismic source zones and special consideration of rare large eastern earthquakes; explicit definition of crustal fault sources in the Yukon Territory and offshore western margin faults (north of Cascadia) based on GPS observations and paleoseismic slip rates; catalogue magnitudes expressed consistently in terms of moment magnitude for improved magnitude-frequency statistics; and the use of a suite of representative backbone ground-motion models. The GSC is now working towards the 2020 building code model. A major element will be changing from 1980s-era FRISK88 software to the OpenQuake-engine for hazard computation. To ensure comparability we have performed comprehensive tests using our 2015 model implemented in OQ. Without adjustments for how some elements of the model are treated by the two codes, the engines give results within 2-3% for much of Canada, but up to 15% different in some places. When adjustments are made for magnitude-recurrence distribution, integration slice size, cutoff distance, and floating-rupture distribution along fault sources, the differences reduce to <2-3% everywhere.

*S07-3-02
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S07. Strong ground motions and Earthquake hazard and risk

A Novel Geodetic-based Probabilistic Seismic Hazard Model for Iran

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This study develops a preliminary probabilistic seismic hazard (PSHA) model for Iran using seismic moment rates obtained through combined analysis and modeling of Iranian seismic, geodetic, and geologic data. PSHA has previously been based on the extrapolation of the large earthquakes frequency from rates of small ones that recorded instrumentally in 50 – 100 year-long earthquake catalogs. Unfortunately, factors such as incomplete catalogs, long term return period of large and strong earthquakes and short term catalog give not reliable results. Therefore the hazard analysis that is based on inputs which leads to less uncertainty is necessary. For some place in the world such as California, Canada, Japan, New Zealand and Italy, geodetic and geological data is used in hazard analysis by researchers. The results show that estimated earthquake rates are larger than those derived from earthquake catalogs. In this regard, using novel and alternative approaches in hazard assessment will greatly improve our knowledge and many questions about spatial-temporal distribution of earthquakes could be answered. Moreover, the ground motion parameters uncertainty as hazard analysis output will be reduced. In a recent study (Khodaverdian et al. 2015) the long-term deformation of the Iranian Plateau is estimated by the Neokinema software using updated Iranian database including latest fault traces, geologic fault offset rates, GPS velocities, principal stress directions, and velocity boundary conditions. Accordingly in this study, for the first time an independent hazard estimate for the Iranian Plateau will be obtained through the seismic moment rate required to accommodate current rates of deformation from geodetic and geological data. The estimations could be compared with the results of traditional seismic-based hazard analysis. The final outcomes are time-dependent and time-independent probabilistic seismic hazard models.

*S07-3-04
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground M
otion / S07. Strong ground motions and Earthquake hazard and risk

ANALYSIS OF RESPONSE SPECTRA OF CHARACTERISTIC GROUND MOTIONS RECORDED IN NORTH EAST INDIAN REGION

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The response spectra are influenced by the local site conditions and regional geology. For various categories of rock sites like hard rocks (Proterozoic period), sedimentary rocks (Tertiary period) and alluvium (Quaternary period) exhibit this effect for North East (NE) Indian region. This has been analyzed using 195 strong ground motion histories from 45 earthquakes occurred in NE India having the magnitude range of Mw 3.5 to 6.9 recorded from 2008 to 2014 on strong motion network of India. The ground motion is amplified at higher frequencies for stations located on hard rock while for stations located on alluvium sites are amplified comparatively at lower frequencies. Also the sites located on hard rock show lower spectral acceleration than alluvium sites. The acceleration response spectra in the current Indian code designed for the entire country is applicable for all rock types for the study area. The effects of important ground motion parameters like magnitude, distance, local geology and site conditions on acceleration response spectra are studied. The response analysis constitutes the importance in representing the seismic hazard assessment of an area especially for NE Indian region as this falls in the zone V on the seismic zonation map of India. This study is important for the seismic hazard assessment of the NE India which is an active plate boundary having complex seismotectonics.

*S07-3-05
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TIME-DEPENDENT SEISMIC HAZARD DUE TO MINING-INDUCED EARTHQUAKES IN GAUTENG, SOUTH AFRICA

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A time-dependent probabilistic assessment of the seismic hazard along the densely populated northern rim of the Witwatersrand Basin of the Gauteng Province, South Africa, is described. Seismicity in this region is mainly induced by deep gold mining and the flooding of worked-out mines. Seismic hazard assessment in the gold mining regions has not been incorporated in global projects such as the GSHAP, although the seismicity related to the gold mining activities accounts for about 90% of the seismicity of South Africa. Time-dependent seismic hazard estimates are given in terms of peak ground acceleration and 5% damped response spectra at periods, 0.1 s, 0.5, 1.0 and 2.0 s for 10% probability of exceedance in 50 years (475 year return period) for two different periods named Period A (1970 - 2004) and Period B (2005 - 2015). Seismic hazard estimates are higher in Period A owing to higher activity rates than in Period B. The highest estimated PGA value was approximately 0.250 g for a return period of 475 years in the western part of the region in Period A while the corresponding estimated PGA value was 0.206 g for a return period of 475 years in the same region in Period B. The spectral acceleration values also decreased from Period A to Period B. It was observed that the Far West Rand seismic zone contributes more hazard in the study region, followed by the West Rand seismic zone and then the East Rand seismic zone. The Central Rand seismic zone is the least active seismic zone and contributes least to the hazard of the study region. The hazard estimates are higher in the western parts of Johannesburg than in the eastern parts of Johannesburg.

*S07-4-01
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S07. Strong ground motions and Earthquake hazard and risk

Rapid estimation of ground-shaking maps for seismic emergency management in Turkey

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Strong ground-shaking mapping soon after a moderate-to-large earthquake is crucial to recognize the areas that have suffered the largest damage and losses. These maps have a fundamental role for emergency services, loss estimation and planning of emergency actions by the Civil Protection Authorities. This is particularly important for the Eastern Mediterranean areas with high seismic risk levels, such as the Turkey. Rapid (3-5 minutes) generation of maps of instrumental ground-motion and shaking intensity is accomplished through advances in real-time accelerometric data acquisition combined with newly developed relationships between recorded ground-motion parameters and expected shaking intensity values.

Taking advantage of the National Strong-Motion Network (TR-NSMN) of Turkey which belongs to Earthquake Department of the Disaster and Emergency Management Authority (AFAD, Ankara) of the Turkish Prime Ministry, we have implemented the algorithm for rapid estimation of ground-shakings soon after moderate-to-large earthquakes occurred in Turkey.

Estimation of shaking over the Turkey is obtained by the spatial interpolation of the measured ground motions with geologically based frequency and amplitude-dependent site corrections. Production of the maps is automatic, triggered by an earthquake (M>4.0). Maps are made available within several minutes of the earthquake for public and scientific needs. The algorithm produces ground-shaking maps by highlighting its ability to predict peak ground-motion parameters of large magnitude earthquakes (Corresponding Author, O.Polat)

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otion / S07. Strong ground motions and Earthquake hazard and risk

Development of a pilot seismic risk assessment for British Columbia, Canada, through the application of Global Earthquake Model's OpenQuake

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The Geological Survey of Canada (GSC) has employed Global Earthquake Model's (GEM) OpenQuake as a potential tool for undertaking a national-scale earthquake risk assessment, beginning with a provincially-focussed assessment of British Columbia (BC), the most seismically hazardous region of the country. While the GSC has traditionally focused on probabilistic seismic hazard models, we endeavour to provide the engineering and emergency management communities with a suite of deterministic scenarios, evaluations of secondary hazards such as tsunami and liquefaction, and impact assessments. There are numerous feasible scenario earthquakes along British Columbia's tectonically active west coast with the potential to cause extensive damage. A small number of these will be presented, including an M~7.0 event along the recently profiled extension of the Devil's Mountain Fault just off the City of Victoria's waterfront, and a megathrust earthquake of M~9.0 with tsunami along the Cascadia Subduction Zone, off BC, Washington, Oregon and northern California. The resulting scenarios provide anticipated ground motions which are applied to vulnerability data (including site conditions, infrastructure and population exposure) to develop impact models. These outputs are crucial for effective emergency planning, risk mitigation measures and disaster management.

Ground motion predictions in the backdrop of recent claims for mega earthquake in Bangladesh

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The main plate boundaries between north moving Indian plate and the Eurasian plate have been traditionally depicted in seismo-tectonic maps to the east and north of Bangladesh. However, recent seismological studies claim the plate boundary to be extended well inside Bangladesh, and that the major cities of the country may face the risk of a mega earthquake with a magnitude between 8.2 and 9.0. This claim can drastically redefine the seismic zoning map of Bangladesh with ground motion values way above present building codes and way beyond our present perception.

This paper attempts to investigate the possibility and implication of a mega earthquake in the backdrop of such claim. Seismic hazard assessment studies incorporating such mega earthquakes have been conducted, results indicate severely high ground motions for major cities of Bangladesh including the capital city of Dhaka.

A critical review of literature on historical earthquakes affecting the country is done. A rationale for the location and magnitude of the maximum considered earthquake (MCE) is developed through careful review. Ground motion predictions using such MCE have been conducted using both probabilistic and deterministic seismic hazard assessment approaches. Finally the author's perception of the possibility of mega earthquakes and the way forward in seismological research is presented.

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Automatic detection of earthquakes, quarry blasts, rockfalls and avalanches on the Swiss permanent broadband network

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In common observatory practice, seismic events are detected automatically using a classical STA/LTA trigger. Then, a trained expert manually assigns a specific seismic signal class such as tectonic event or quarry blast to verified detections. However, this approach absorbs manpower and happens generally with considerable time-delay. To overcome these problems we test an automatic classification approach on the Swiss permanent broadband network. The approach is based on a probabilistic description of the signals, called hidden Markov models, that allows the robust identification of corresponding signals and has been successfully applied in various environments. The automatic system is set up at 15 stations of which most are located in alpine regions. Once a transient is detected by the preceding trigger, the signal is fed into the automatic system and labeled as one of the following signal types: earthquake, quarry blast, rockfall, avalanche or noise. So far, the procedure is tested on a data period of one year. To evaluate the system performance automatically and manually assigned labels are compared. Achieved results show large differences between individual stations. While at some stations classification rates of up to 95 % are achieved, classification rates are much lower at other stations. The overall performance can be further improved by using the complete network information. For this, the classification results of different stations needs to be combined. We present various approaches to combine the outcome of the automatic system dependent on source-receiver distance and confidence of classification result. A majority based voting system completes the post processing. In the next step, we aim to detect signals directly on the continuous data stream, in order to avoid missing small local events due to the preceding trigger algorithm. The performance provides a base for deciding about implementation of an early information system.

Evaluation of the P-wave detection method using higher order statistics

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Detecting P-wave onsets in on-line processing is one of the important components for the real-time seismology. Conventionally, the STA/LTA method (the ratio between short-time average and long-time average) has been widely used for the P-wave detection (Allen, 1978). Since this method is reasonably robust and computationally less expensive, it has been used for long years, and the trigger time is used for the estimation of the location of earthquakes.

The P-wave detection method using higher order statics has been attracted researchers recently. The key of the method is to identify the change of distribution of amplitudes. In general, seismic noises tend to follow the Gaussian distribution. However, when a seismic signal arrives and the amplitude suddenly increases, the distribution of the amplitude becomes skewed. This change of distribution can be measured by the kurtosis, which is the forth moment of the data divided by the square of the variance. The kurtosis is zero for the Gaussian distribution, and it increases as the distribution is away from the Gaussian.

We applied this method to the strong motion dataset after the Tohoku earthquake in March 2011. The results are compared with the P-wave arrival time estimated by the STA/LTA method, which showed the arrival times estimated by the kurtosis approach was closer to the manually detected P-wave arrival times.

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Simulation of Strong Ground Motions in and around Iwaki City, Fukushima Prefecture, using Pseudo Point-source Model

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After the 2011 Mw9.0 Tohoku earthquake, a great number of aftershocks occur near the source region off the Pacific coast of eastern Honshu. We deployed a dense temporary seismic array consisting of 16 stations in Iwaki city, Fukushima prefecture from November 2014 to September 2015. During the observation period, at least 100 felt earthquakes (Mw in the range of 3.5-7.9) including 75 intraslab and interplate earthquakes along the subduction zone were detected. Previously we applied spectral inversion method to the event data and estimated site amplification factors at each station as well as seismic quality factor (Hayashida et al., 2017). In this study we performed spectral inversion method again by adding event data from K-NET (six stations) and KiK-net (three stations) of National Research Institute for Earth Science and Disaster Resilience (NIED) in and around Iwaki city, and strong motion data of Building Research Institute (BRI) recorded at basement floor of Iwaki city hall, during the same observation period. To perform the inversion, several constraints (rock site assumption, proposed site amplification model, proposed attenuation model or source spectra for selected aftershocks) were employed and we found that the inversion with proposed site amplification model (at K-NET FKS011 station) provides reasonable results. Next we simulated strong ground motions with the pseudo point-source model (Nozu, 2012) using modeled source spectra, the estimated quality factor and site amplification factors for the mainshock of the 2011 Tohoku earthquake and the 2016 Fukushima earthquake (November 22, Mw7.0). The seismic source spectra are modeled using the omega-square model from available source models with phase characteristics of the selected subevents (point source) from our dataset. The synthetic waveforms and its Fourier spectra of S-wave portions show reasonable agreements with observed ones in the frequency range between 0.2 and 10 Hz.

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Inversion seismic parameters model for stochastic ground motion simulation in Taiwan

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Stochastic ground motion simulation technique (Boore, 1983; Boore, 2003) is useful tool to get synthetic ground motions for future possible earthquakes when applying suitable seismic parameters. The parameter models are varied within different regions due to difference in seismogenic structure. Regional parameters used in stochastic simulation that need to be checked are including stress drop, Q, geometric spreading, kappa, site transfer function etc. Parameter models for stochastic point source or finite fault simulation in previous Taiwan researches are usually collected each piece of seismogenic parameters from different studies and composed them together to deal with prediction problems (Sokolov et al., 2000; Sokolov et al., 2001; Sokolov et al., 2009; Huang et al., 2017) or inverted parameters together but some of the path attenuation relation might are far from traditional imagination about wave propagation tectonics in Taiwan (D'Amico et al., 2012).
In this study, seismological records from TSMIP rock sites (Vs30 within 600-900 m/s) will be separated into shallow crust earthquakes and intraslab earthquakes for parameter inversion for shallow and deep events. Initial path attenuation models will be fixed first to solve other parts of the parameter setting. The inverted results could have more confident that all of them are goes together and fix the Brune's spectrum (Brune, 1970) assumed in stochastic simulation technique with physical meanings of each of the parameters but not composed ones. The inverted model could be applied to study regional difference of different area such as Taiwan against Japan or California region when comparing seismograms in different regions.

Keywords: seismic parameters, stochastic ground motion simulation, Taiwan

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Strong ground motion simulations for potential earthquakes around Taiyuan, China based on dynamic rupture sources

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Using the curved grid finite-difference method, we develop dynamic spontaneous rupture models of earthquakes on the Jiaocheng Fault (JF) near Taiyuan, which is the capital and largest city of Shanxi province in North China, and we then model the wave propagation and strong ground motion generated by these scenario earthquakes. A map of the seismic hazard distribution for the potential M7.5 earthquake is given based on dynamic rupture and true 3D modeling. The tectonic initial stress fields derived from the inversion of focal mechanisms of history earthquakes, a non-planar fault, and a rough surface are considered in the dynamic rupture simulation. Base on the geological structure of the Taiyuan basin, the normal faulting with a dipping angle of 60 degree is implemented for the scenario earthquake simulations. The largest uncertainty of the potential earthquake in the JF zone is the hypocenter. Four cases are used to nucleate the earthquake at different locations. Using these dynamics rupture sources for JF, we further simulate and analyze both the seismic wave generated by the scenario earthquake and the strong ground motion. It is found that the low-velocity media of the Taiyuan basin redistribute the ground motion well. The effects of the regional stress fields on the dynamic rupture and hazard distribution are investigated and discussed further. Moreover, a scenario earthquake, which can cause great damage to Taiyuan City is modeled and analyzed.

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3D numerical modeling of seismic wave propagation and amplification in Qaidam basin

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Qaidam basin is the largest basin within Qinghai-Tibetan plateau with area of ~120,000 km2. Maximum thickness of basin sediments is about 12 km. Seismograms recorded by International Deep Profiling of Tibet and the Himalaya Phase IV (INDEPTH IV) seismic stations during 2008 show clear spatial variations and seismic ground motion amplification was observed in several events.
In this study, we constructed a three-dimension seismic wave velocity model of Qaidam basin based on previous studies, including three sedimentary layers from Paleogene to Quaternary and perform 3D numerical modeling of seismic wave propagation in Qaidam basin with 3D Finite-difference method (FDM). We employ a high-performance parallel supercomputer to simulate seismic wave propagation in the area around the large Qaidam basin. Based on modeling, we will explain the mechanism of the development of observed long-period surface wave in the data and dramatic amplification of ground motion in the Qaidam basin.
Three different models, 1) model only contains crust with flat surface, 2) crust model with topography, 3) model contains sedimentary layers and topography over crust, were simulated to evaluate the effects on seismograms in basin. Based on simulation, slightly amplification from 0.4 -1.0 Hz caused by topography in vertical component of stations installed in mountain area (higher altitude) around basin. Considerably amplification by sedimentary layer from 0.1 - 0.8 Hz in three components of stations in the middle of basin.
2008 Da-Qaidam Mw6.3 earthquake together with two aftershocks and 2001 Kunlunshan Mw7.8 earthquake around Qaidam basin were simulated to estimate amplification effects of basin on earthquake with different magnitude and with different azimuth.

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Strong-Motion Observation Network in the Philippines

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Issues raised after the July 16, 1990 M7.8 Luzon Earthquake and public concern over a possible large earthquake that may occur along the Valley Fault System that transects Metropolitan Manila prompted Philippines Institute of Volcanology and Seismology (PHIVOLCS) to establish a Strong-Motion (SM) observation network in the Philippines in 1992. The SM network initially consist of only four stations operating within the metropolis and this has expanded to a network of ten stations by early 2000. Since then, the network has expanded its coverage and is presently composed of thirty-five and twelve instruments in cities in Luzon and Davao respectively, with plans to cover other areas of the country. The establishment of this network aims to truly record earthquake ground motions especially near active faults and areas with concentration of population and different types of buildings.The Kinemetrics K2 strong-motion accelerograph is the major instrument of the network. The recording sensor is Episensor triaxial force balance accelerometer mounted orthogonally in one small convenient package within the recorded box.

Some of the significant earthquake events that have been recorded by different stations of the SM network include the 1999 M6.8 Hermana Mayor Island Earthquake, the 16 June 2012 M6.0 Zambales Earthquake, the 31 August 2012 M7.6 Offshore Eastern Samar Earthquake and 25 June 2014 M5.8 Occidental Mindoro Earthquake. Records of these events exemplify varying site responses at different geologic conditions.

Recorded events are initially analyzed and catalogued in a databased of digital strong ground motion together with station information and important operational dates. The strong-motion database will serve as a centralized resource for accelerograms of relevant Philippine earthquakes to support scientific research, earthquake engineering and the updating of the National Structural Code of the Philippines.

HVSR site classification method for Chinese seismic code based on Japanese strong motion data

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The local site condition is a very important factor for strong motion data. We performed the site classification of the strong motion stations for China National Strong Motion Observation Network System (NSMONS), by using an empirical Horizontal-vertical spectral ratio (hereafter, HVSR) method. Due to not enough Chinese strong motion data and borehole, we firstly selected all needed information from Japanese KiK-net and statistically assigned the mean HVSR curve of the site classification (CL-I, CL-II, or CL-III) defined in the Chinese seismic code. The mean the HVSR curve for each site class was computed using Chinese strong motion recordings captured during the period 1996–2012 . For each strong motion stations, the station HVSR curves were compared with those proposed by Zhao et al. (2006a) for four types of site classes (SC-I, SC-II, SC-III, and SC-IV) defined in the Japanese seismic code (JRA, 1980). It was found that an approximate range of the natural period could be identified by the predominant peak of the HVSR curve for the CL-I and SC-I sites, CL-II and SC-II sites, and CL-III and SC-III + SC-IV sites. Meanwhile, an empirical method of Chinese site classification was proposed based on comprehensive consideration of peak period, amplitude, and shape of the HVSR curves. 178 NSMONS stations were computed based on recordings from 2007 to 2015 and the sites classified using the proposed method. The mean HVSR curves were re-calculated for site classes and compared with those from KiK-net data. It was found that both the peak period and the amplitude were similar for the HVSR curves derived from NSMONS and KiK-net data, implying the effectiveness of the proposed method in identifying different site classes. It is also found that this classification has a good agreement with site classes based on 81 borehole data in China, which indicates that this site classification results are acceptable.

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Nonlinear Site Response at KiK-net KMMH16 (Mashiki) and Heavily Damaged Sites during the 2016 Kumamoto Earthquake, Japan

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Severe ground motion damages occurred in the downtown area of the Mashiki town, Kumamoto Prefecture, during the 2016 Kumamoto earthquake, Japan, and several heavily damaged zone appeared in the center of the downtown. Nonlinear site response for the first (14th Apr., 2016) and main shocks (16th Apr., 2016) is important factors to explain the reason why the heavily damaged zone appeared. We analyzed the soil nonlinearity by using the surface and borehole records at KiK-net KMMH16 (Mashiki) station. Optimal S-wave velocity models clearly depended on the amplitude of input ground motions. Strain dependent shear stiffness and damping ratio were estimated to explain the S-wave velocity dependence on the input motion amplitudes. We conducted nonlinear analyses at KMMH16 site on the basis of the nonlinear model. The synthetic surface ground motions agreed well with the observed ones, especially at S-wave amplitude and phase for the first and main shocks. In addition, we also conducted the same analyses at TMP3 site, which was located in the heavily damaged zones. The synthetic motions well represented the observed ones, and difference of spectral accelerations was well explained by the analyses. The results indicated that the soil nonlinearity played a big role to cause the difference of ground motions, and thus the damaged zone appeared in the downtown of the Mashiki town.

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Long-period later phases observed in the Echigo Plain, Japan during the deep earthquake in the west off Ogasawara Islands of May 30, 2015

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On May 30, 2015, a deep earthquake of magnitude 8.1 occurred at a depth of 682 km off the west of the Ogasawara Islands. In case of a deep earthquake, the incident wave to a basin structure can be regarded as a body wave, and therefore the surface wave generated at the basin edge can be evaluated separate from incident surface waves. In addition, since almost the same incident wave can be expected for inside and outside of the basin, it is considered to be effective for evaluation of site factor. The Echigo Plain, Japan is known as an area where the seismic bedrock is deep and long-period ground motion is dominant. To see the influence of the basin structure, we examined the waveform change along the line from Mt. Yahiko to the Echigo Mountains across the Echigo Plain. The waveform of S wave part was common to all observation points. On the other hand, no significant later arrivals were recognized in the waveform of the mountain region, whereas there were complicated later arrivals and the duration was long in the waveform of the plain part. Also, it was able to be confirmed that the travel time delay of the S wave by the low-velocity sedimentary layers and the later phases seemed to propagate from the edge to the center of the basin from the comparison of wave traces. Numerical simulations were carried out to confirm the generation of the later phases by the underground structure. For the numerical calculation, a two-dimensional finite difference method was used. The numerical simulation was able to reproduce the amplification of ground motion and the generation of later arrivals in the basin. However, the reproduction of the duration of the ground motion was insufficient.

Revision of 3D Model of the Kanto Basin based on Earthquake Records of MeSO-net

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In recent years, numerous simulations using 3D finite-difference method are performed to predict earthquake ground motions due to large earthquakes. In order to improve the prediction accuracy of earthquake ground motions, Accuracy of 3D underground structure model is one of the important factors. To obtain a 3D Kanto Basin model, Yoshida et al. (2007) estimated the underground structure under 120 K-NET and KiK-net sites in Kanto Basin by using the method of Kobayashi et al., (2005). In this method the horizontal-to-vertical (H/V) spectral amplitude ratios and receiver functions of P wave part of seismic observation records were simultaneously inversed. Then a 3D model of the Kanto Basin was constructed by spatial interpolation using the estimated underground structures and gravity anomaly data. In order to improve the accuracy of this model, we increased estimation points of underground structure utilizing about 200 sites of MeSO-net (Sakai and Hirata, 2009) which were located at 296 sites in Kanto region, and we also used the improved method of Umeda and Kobayashi (2010) which is added H/V spectral amplitude ratio of coda part of seismic observation records to the method of Kobayashi et al. (2005). Then the model was modified by adding the estimated underground structures. Medium earthquakes occurred below the Kanto Basin were simulated using the revised 3D model to compare the calculated and observed velocity waves. By comparing the simulation results from the original model, the influence of addition of estimated underground structures on the improvement of the prediction accuracy was discussed.

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Direct evaluation of site amplification factors based on observed motions of earthquakes and microtremors

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It has been used for more than three decades to characterize earthquake S-wave site amplifications from microtremor Horizontal-to-Vertical ratios (MHVR), although the skepticism has been surfaced through many studies on such a direct substitute after the proposal. To solve the controversy based on the concept of the recently proposed diffuse field assumption, we calculated MHVR as well as those from observed weak earthquake motions (EHVR) and compared fundamental characteristics of the MHVRs and EHVRs with those calculated theoretically from 1-D S-wave velocity structures. Either for MHVRs or EHVRs we found that we can reproduce their fundamental characteristics by the corresponding theories of diffuse field concept. MHVRs and EHVRs share similarities but have significant differences in their shapes, especially after the first peak frequency. This is because MHVR mainly consists of surface waves from surface sources while EHVR consists of S-waves from the bedrock. We then tried to establish a simple method to estimate velocity structures using single-station microtremor records. To that end we compared systematically EHVRs and MHVRs at 100 K-NET and KiK-net sites in Japan and calculated EHVR-to-MHVR ratios (EMRs) to get EMRs averaged over five different peak-frequency categories. We converted MHVRs to “pseudo EHVRs" from EMRs and MHVRs, which are found to have higher correlation with EHVRs than MHVRs. Then we proved that pseudo EHVRs give us similar S-wave velocity profiles than the direct use of MHVRs as substitute of EHVRs. Finally, we calculate average Vertical-to-Vertical spectral ratios (VVR) from the generalized spectral inversion (Nakano et al. 2015) and calculated the average VVRs for the same category of MHVRs. By multiplying VVRs with pseudo EHVRs we can obtain S-wave amplification of earthquakes, which can be favorably compared with actual S-wave amplification factors.

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Shallow shear wave velocity model of Taiwan constructed from Receiver Function Analysis of strong motion stations

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The high seismicity and major tectonic features of Taiwan are resulted from the active collisions. The young and fast orogeny in the island also forms a wide range of alluvium plains and basins that are filled with unconsolidated Quaternary sediment covering the bedrock. The obvious seismic site effect amplifies and extends incident seismic waves and can result in earthquake disasters. Therefore, a shallow velocity model, reflecting the real and complex seismic site effects in these areas, is necessary for ground motion simulation and prediction in Taiwan.
The advantage of the even strong motion stations and numerous records in Taiwan has been taken to apply the Receiver Function (RF) technique to high-frequency acceleration seismograms recorded by Taiwan Strong Motion Instrumentation Program (TSMIP) stations to estimate the shallow shear wave velocity (Vs) structures. In the RF analyses of this study, an average RF of each station was calculated to enhance the converted phases and reduces the inharmonic arrivals. Based on the geological, geophysical, and Engineering Geology Database for TSMIP (EGDT) drilling data, an initial layer model with variable Vs and thickness was assumed to model RF and estimate Vs profile of a station by Genetic Algorithm (GA) search. Finally, the one-dimensional shallow Vs profiles of over 700 stations were estimated by RF analysis and forward modeling with GA search. All the results proved that this method is not only effective in teleseismic but also strong motion records to construct a shallow Vs structure of alluvium plain (or basin) overlaying a hard bedrock. Based on the Vs structures estimated in this study, a shallow velocity model of Taiwan was preliminarily constructed for applications of seismology and earthquake engineering. In addition, the results were also compared with the Vs30 of EGDT to confirm the site conditions of TSMIP stations and provide important site parameters such as engineering bedrock and Z1.0.

Liquefaction Monitoring and Observations of Excess Pore Pressure Generation During Strong Motion

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Unique dense observations of excess pore pressure generation and dissipation during earthquakes are presented from multiple borehole arrays within ~100 meters of each other in the confined 5-meter thick silty sand layer at the Wildlife Liquefaction Array (WLA), Imperial Valley, California. In what is the most densely instrumented liquefaction array anywhere in the world, continuous recordings of acceleration and pore pressure are providing in situ empirical evidence documenting the range of ground motion and dynamic strain levels at which the onset of excess pore pressure and nonlinear soil behavior begins, augmenting previous case history data, and cyclic tri-axial and centrifuge laboratory testing. The observations with depth within the liquefiable layer shows the excess pore pressure develop quickly at the top of the layer just below the impermeable clay cap, and then migrate towards the bottom of the layer as the ground motions subside and the pressure dissipates over the course of minutes to hours depending on the level of ground motion. Confirmation of this behavior is provided by monitoring multiple locations within ~100 meters of each other, with 8 transducers at one location and 5 transducers at a second location (both operating for more than a decade now), and 5 transducers at a third location (since 2014). The 5 sensors at the third location densely cover the upper two meters of the liquefiable layer, while the sensors at the other two locations sample the top, middle, and bottom of the layer. A comparison of these recordings to demonstrate the spatial variability both with depth in the liquefiable layer as well as within the 100-meter areal distance at the field site with be presented. This spatial variability is analyzed with respect to both the fine-scale heterogeneous soil properties (percent fines, relative density, saturation) as well as with respect to installation methods and site improvements to potentially increase liquefaction resistance.

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Temporal nonlinear site response during Kumamoto Mw7.0 earthquake inferred from borehole strong motion data

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The Mw 7.0 Kumamoto earthquake (Japan) occurred on 15 April 2016 – 16:25 UTC. Using both borehole and surface ground accelerations recorded by Japanese Strong Motion Network KiK-Net, we investigate temporal changes of nonlinear site response in the shallow crust associated with Kumamoto main shock and the triggered Mj 5.7 event. We compute the spectral ratios of windowed records from a pair of surface and borehole stations, and then use the sliding-window spectral ratios to track the temporal changes in the site response of various sites at different levels of peak ground acceleration (PGA). Our preliminary results show clear drop of resonant frequency of up to 60% during the main shock at 8 sites with PGA from 200 to 1000 Gal. We investigate the percentage drop of peak frequency and peak spectral ratio during the main shock at different PGA levels.

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DETERMINATION OF DEEP SUBSURFACE SHAREWAVE VELOCITY STRUCTURE IN THE CENTRAL PART OF THE KATHMANDU BASIN, NEPAL USING BROAD BAND SEISMOGRAPH ARRAYS FOR LONG PERIOD MICROTREMOR

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We conduct microtremor array exploration in the central part of the Kathmandu Valley, Nepal assuming the deepest part of the basin in order to determine the shear wave velocity structure of deep sedimentary layers for strong ground motion simulation within the frame work of SATREPS (JST - JICA) project for 5 years. The four seismographs used are consist of the broadband seismometer CMG40T (Gularp) and the digital data logger LS8800 (Hakusan) for exploration as deep as 500 – 600 m using long period microtremor (ambient noise), the power of which is weak due to a distance as long as 700 Km from the nearest ocean Bay of Bengal. Up to Feb. 18 2017, the following three arrays have been performed. First an irregular shape array consist of three deployments was performed at and around the strong ground motion observation site in the office building of Department of Mines and Geology, Lainchaur (DMG). A seismograph was installed and worked for more than three nights at DMG and other three were set for overnight measurement, at different sites every night, within a distance of approximately 1.2 Km situated at Narayanhiti Durbar Museum, Durbar Marg and Nepal Police Head quarter, Naxal in the single storey buildings or on the open ground during December 2016. Second an array consists of two almost equilateral triangular deployments and an irregular quadrilateral one has been deployed inside Singhadurbar an administrative center of Nepal government and also the third at and around the gas well point of DMG in Teku during February 2017. Preliminary analysis showed a clear peak of the power spectra of the horizontal components at a little longer period than 3 seconds that has not been detected by the microtremor observation using accelerometer due to the low power of long period microtremor.

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The spatial variability of the directionally dependent microtremor horizontal-to-vertical spectral ratios at the boundary of the basin edge in Uji, Japan

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Directionally dependent microtremor horizontal-to-vertical spectral ratios (MHVRs) have been observed in Uji, Japan, close to the basin edge which is formed as a result of the reverse fault movement of Obaku fault, in the south-eastern part of Kyoto basin and the directionally dependent MHVRs are assumed to be a result of the effect of the two dimensional basin structure from on the theoretical MHVR calculated based on the diffuse field assumption (Matsushima et al., 2014). The study was focused on the MHVRs where the directional dependence of the MHVRs were very clear.
In this study, we have conducted microtremor observations in a wider area compared to the previous studies in order to investigate the spatial variability of the directionally dependent MHVRs in and around the target area. We extended the observation area to sites further away from the basin edge, i.e. closer to the central part of the basin, and sites up the hills to the hanging wall side of the Obaku fault. The observed MHVRs showed that if the site is further enough from the basin edge it does not show much directional dependency, where we can assume that the subsurface structure is flat-layered. On the other hand, if we go up the hills, the peak diminishes as predicted by numerical calculations by Matsushima et al. (2014). These information obtained from MHVRs can be used to specify the detailed shape of the basin edge combined with numerical calculations of MHVRs assuming the diffuse field.

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Ground motion pattern generated by the undercrustal seismic source of the Vrancea region, Romania

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The seismogenic source of strong earthquakes (Mw > 7) from the bend of the Southeastern Carpathians is located in the undercrustal lithosphere, in a complex tectonic setting.
A modest number of strong motion records – all analogue – is presently available for Vrancea events with moment magnitude above 6, due to the low occurrence rate of these seisms, as well as to the poor seismic instrumentation in the region, before 1980. The strongest digitally recorded intermediate-depth earthquake is the Mw 6.0 event of October 27, 2004.
Detailed macroseismic maps are available for the strongest Vrancea seisms which occurred at the end of the XXth century (4 earthquakes with moment magnitude 7.4, 7.1, 6.9, and 6.4, respectively). They all display a peculiar shape of the isoseismals, with a pronounced asymmetry. The few existing instrumental records support these features.
During the past decades the Romanian seismic network has continuously been developed and upgraded; at present, it covers the entire country, and comprises 118 permanent digital stations equipped with 3-component accelerometers.
Taking advantage of the significant amount of recently collected high-quality data, we examine the space distributions of the ground motion parameters (PGA, PGV) yielded by several tens of moderate-sized undercrustal earthquakes, with Mw between 4.0 and 5.6. Their hypocenters cover well the seismogenic zone. The focal mechanisms indicate – with few exceptions – reverse faulting, nevertheless, the orientation of the nodal planes show a notable diversity.
The individual ground motion distributions display noticeable differences, but also important common characteristics – largest parameter values in the Extra-Carpathian area, rapid decrease of ground shaking towards the Intra-Carpathian region. The study evidences that the local and regional geological conditions control the ground motion pattern to a larger degree than the source parameters (magnitude, mechanism, hypocenter location).

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Strong ground motions due to the 2016 mid Tottori prefecture earthquake, Japan

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An earthquake with Mj 6.6 hit mid area of Tottori prefecture, Japan on October 21st., 2016. In the area, earthquake swarms have been activated since mid October in 2015. Large number of seismometers installed by the prefectural government, JMA(Japan Meteorological Agency), NIED(National Institute for Earth Science and Disaster Resilience) and Tottori University, observed strong ground motions in the area. We also conducted aftershock observations just after the main shock at several temporary sites in the area with housing damages. From prompt analysis of the observed strong motions, it is understood that the ground motions were affected strongly by local site conditions, especially their predominant period caused by sedimentary response. The observed predominant periods at strong motion sites agree well with those estimated by previously conducted microtremor observations by ourselves. We will report characteristics of the observed ground motion and structural damages due to the earthquake considering effect of surface geology in the area.

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Peculiar strong ground motions from the very deep (h=680 km) Mw 7.9 Ogasawara Islands earthquake of 2015 May 30

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The Mw 7.9 earthquake beneath the Ogasawara Islands on 2015 May 30 at 6780 km depth, produced an anomalously large shock over Japan. This event is about 100 km deeper than other seismicity in the vicinity and produced a distinctive pattern of ground motion.
Usually deep earthquakes in the subducting Pacific slab near Ogasawara develop anomalously large ground motions along the east coast of Honshu due to an efficient slab waveguide effect for high-frequency (f > 1 Hz) signals. However, the waveforms of regional distances (1000 - 2000 km) for the very deep event indicate that the large ground acceleration arises from relatively low-frequency (f < 1 Hz) S-wave pulses and following long-period (f < 0.1 Hz) signals with long tails. The arrival of the slab-guided high-frequency signal was very late and weak compared with ordinary slab events.
Numerical simulation of seismic wave propagation shows how the deep source outside the main slab affects the wavefield. S waves from the source travel upwards and impinge on the crust at around 1000 km epicentral distance with similar slowness to P in the crust and produce strong S-to-P conversions at the free surface. The converted P waves are trapped in the crust with multiple Moho and surface reflections interfering to produced a long-period PL wave. The S-PL wave can travel substantial distances in the crust. Weak slab-guided S waves from the very deep event are also transferred injected into the crust and continue as an Lg wave in the crustal waveguide.
The very deep event produces a broader distribution of strong ground motion, but much stronger concentrated effects with potentially disastrous consequences can arise due to much enhanced slab waveguide effect when a very large event lies in the core of the slab.

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Slip Rates Inversion of 3-D Faults around Ordos Constrained by GPS and Leveling Observation

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Development of geodetic observation shadows light to inversion of crust motion which is crucial to seismic hazard potential analyze. Vertical fault models are always used for inversion in traditional researches, but we find inclined faults will result in different near-field surface velocity.Therefore, we first construct a 3-D fault model of Ordos by using micro-earthquake relocation data. GPS data and vertical high-resolution leveling data are implied in this geodetic inversion and they are processed by our designed method called　‘Pair Difference'. Leveling data is essential for the fault's dip-slip motion is more sensitive to leveling data than GPS data. By using data and inversion method, we remove the continuous fault slip rate constraint which is traditionally used in geodetic inversion and derive an overall and detailed fault slip rate map of Ordos. Furthermore, we point out the areas with high seismic risk by utilizing the inversion results and historical earthquake catalog to calculate seismic deficit.

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Near-field long-period strong ground motion during the 2016 Mw 7.0 Kumamoto earthquake

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The mainshock with Mw 7.0 of the 2016 Kumamoto earthquake occurred at 01:25JST on April 16, 2016 along the Futagawa fault zone and the northern part of the Hinagu fault zone. Surface breaks caused by the mainshock were found associated with Futagawa-Hinagu fault system by field surveys (Earthquake Research Institute, 2016). Near-field strong motions with high accuracy during the earthquake were recorded by the NIED strong motion network (K-NET and KiK-net) and the JMA and local-government seismic-intensity network. In particular, there are located two stations, Mashiki town-hall (MTH) about 2 km and Nishihara village-hall (NVH) about 1 km close to the surface traces along the Futagawa fault zone (Iwata, 2016). We simulated the ground motions of the 2016 Kumamoto earthquake using a characterized source model consisting of strong motion generation areas (SMGAs) based on the empirical Green's function (EGF) method. The locations and areas of the SMGAs were determined inside the seismogenic zone deeper than 3 km through comparison between the synthetic ground motions and observed motions. The synthetic ground motions obtained using the EGF method agree well with the observed motions in terms of acceleration, velocity, and displacement within the period range of 0.1 to 3 s (Irikura et al., 2017). However, the long-period motions more than 3 s seen at MTH and NVH are not well simulated against the observation. We put a long-period motion generation area near Earth surface above the SMGA to produce long-period ground motions. The ground motions at MTH and NVH show clearly the fling steps as shown in near-field ground motions during the 1992 Landers earthquake (Hisada and Bielak, 2003). We assume a long-period (about 3 s) modified-ramp-functions as slip velocity time functions on the LMGA learning from the inversion results of Kubo et al. (2016). The synthetic ground motions as a sum of ground motions from the SMGA and those from the LMGA agree well with the observed ones.

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Influence of vertical acceleration in seismic hazard. Observations of earthquakes in Ecuador

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The effect of vertical component is usually neglected in the design process of new structures. Some building codes, such as the Ecuadorian Standard (NEC-15), suggest a value of 2/3 of the horizontal component when the structure is located near an active fault; however, the definition of “near" remains under discussion.
Using the data recorded by the local strong motion network since 2009, a comparison with ground motion prediction equations (GMPEs) for the vertical component is performed. Data show that low-magnitude crustal events can generate vertical accelerations comparable to the ones observed on the horizontal counterparts. In this article, the city of Quito- Ecuador is chosen as a case study to demonstrate the effect of vertical acceleration in existing buildings. For this city, several earthquakes between 4.5 and 5.1 magnitudes, generated by a local fault system, have produced high accelerations. On the other hand, records of subduction earthquakes, including the 2016 megathrust Muisne event, are used to define appropriate distance metrics.

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Validating a source model for the 2011 Tohoku Earthquake using a dense strong-motion array

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After the 2011 Tohoku, Japan, Earthquake, the importance of reliable predictions of strong ground motions for mega-thrust earthquakes has become more widely recognized than ever. For this purpose, it is essential to validate source models and simulation methods using the strong-motion data of the Tohoku earthquake. From engineering point of view, one of the most striking features of strong ground motions of the Tohoku earthquake was the generation of pulses; strong ground motions in the frequency range from 0.2 to 1 Hz observed at stiff stations along the coast of Miyagi through Ibaraki were characterized by distinctive pulses (Nozu et al., 2012). The importance of the pulses is that they appeared in the frequency range relevant to structural damage.
A source model called the "SPGA (Strong-motion Pulse Generation Area) model" was developed to explain strong ground motions from the Tohoku earthquake including the pulse (Nozu et al., 2012). The source model involved nine subevents with relatively small size (on the order of several kilometers), located off the coast of Miyagi through Ibaraki. This source model satisfactorily reproduced strong ground motions of the earthquake along the coast of Miyagi through Ibaraki including the pulses. In contrast, source models with larger subevents (SMGAs) with a size of tens of kilometers failed to reproduce those pulses.
Although the SPGA model was already validated using strong motion records along the coast, it is necessary to further investigate the reliability of the source model especially by using records from dense strong-motion arrays such as the Small-Titan (Kamiyama et al., 1999). In this study, the SPGA model will be applied to simulate strong ground motions at 17 Small-Titan stations and its performance will be discussed.

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Features of long-period spectrum of SMART-1 array strong motion records

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Long period features of strong motion on the same kind of sites are analysed using the records of digital accelerographs deployed in SMART-1 array of Taiwan. Although the differences of epicentral distances for different stations are small for the same earthquake, the short period spectral components of accelerograms are different obviously, while the long period spectral components are same mainly. The effects of magnitude and epicentral distance on long period spectral components are not so stronger as for short period components. Finally, the average spectrum for SMART-1 array of Taiwan is compared with the design spectra of the new seismic design code of buildings. Some useful conclusions are summarized as follows.
(1)For accelerogram of the same class site at the same epicentral distance of one earthquake, there is some significant difference between the acceleration response spectra in the short period parts, but little difference in long period parts. The effects of exiguous difference of the local site and other random factors can be neglected in the long period parts.
(2)For accelerogram at the same place from difference earthquakes, there is some significant difference between the periods at which the peak values the acceleration response spectra, and values of spectra are also different in long period parts. That is to say, it is maybe not proper that the characteristic period of design spectra is adjusted only according to the site conditions.
(3)From the shape of average spectra for soil sites, it is obviously that the declined speed of long period parts is slower than that of short period parts. It shows that it is reasonable that the declined segment of design spectra is divided into two parts in the revision of Seismic Design Code of Buildings. and on the other hand, the characteristic period of design spectra should be extended further.

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Processing Strategy On Strong Motion Records Of Bizarre Waveforms

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Strong motion records are the first-hand data and precious indeed for research on earthquake engineering, which play an important role in improving structural seismic design, rapid earthquake-intensity reporting and earthquake early warning. However, there are some abnormal data in strong motion records, which reduces the application confidence of the observed data so as to affect the conclusion of scientific research. So, a rich set of strong motion records are analyzed in some typical earthquakes domestic and abroad in this paper. Four kinds of abnormal phenomena on the acceleration waveform are revealed, such as spike, asymmetric waveform, obvious baseline drift and strong motion records packets separation. Then reasonable recognition and processing approaches are derived from the preliminary analysis of the generation mechanism for abnormal phenomena. It is shown that spikes can bring ill effect on the rapid earthquake-intensity reporting and so on, so it should be identified with ‘jerk' method, ratio method and the consistency of the three-component PGA time, and then corrected with average value. For asymmetric waveform, the diversity mechanism is due to instrument pier, instruments and wrong operations. And the area average method and modified moving average method can be applied to identify acceleration records with the characteristics of asymmetric waveform. At the same time, the asymmetric waveform correction for strong motion records from Yibin Gaochang in Wenchuan earthquake is obtained by using the Butterworth low-pass filtering. In addition, two pieces of strong motion record packets can be connected by searching continuous and repeated data. Finally, the method of cumulative adding are used to find the clear baseline drift. At the same time, it is found that the abnormal waveform directly affects the characteristics of time history and frequency spectrum.

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Site-specific investigations in the ongoing renewal project of the Swiss strong motion network (SSMNet)

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In 2009, the Swiss Seismological Service started a project to renew and expand its strong motion network. A total of 100 new stations are planned to be installed until 2019. The goals of the enlargement of the network are a better coverage of regions with increased seismic hazard and risk, a better knowledge of the variability of ground motion and site effects in Switzerland, the study of secondary phenomena such as landslides and liquefaction and finally the verification and improvement of seismic hazard models.
All new stations are free-field and mainly installed in densely populated areas of high seismic risk, but also in more rural areas with relevant historical seismicity.
Installing the new stations is a step-wise process. After the identification of suitable target areas, a first idea of the local site effects is obtained from H/V surveys and geological information. Important infrastructures, such as hospitals, schools or fire departments, where free-field stations could be built, are identified. At these places, test stations assess the local noise level for several days.
Taking all available information into account, the final station locations are decided. After the station construction, passive and active seismic measurements are performed to characterize the site response. Passive seismic array measurements yield Love and Rayleigh wave dispersion curves as well as the Rayleigh wave ellipticity. Where it seems necessary, active measurements with MASW and body-wave refraction are carried out. CPT measurements aim at assessing the potential for nonlinear soil effects and liquefaction.
The inversion of the surface wave properties supplies shear-wave velocity profiles for the soil structure under the strong-motion station. Based on these, the theoretical amplification can be calculated and compared to the observed empirical amplification. In this way, site-specific phenomena such as edge-generated surface waves or resonance can also be identified.

SEISMIC RISK FOR CITIES AROUND THE LAKE KIVU BASIN, WESTERN BRANCH OF THE EAST-AFRICAN RIFTS SYSTEM

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The tectonic conditions of the dome uplift, faulting, volcanism and shallow seismicity around the Lake Kivu (the highest 1462 m) are believed to be the indications of actual rifting and may represent a nascent stage in the development of plate boundary. Since 1997, it was observed in the Lake Kivu Basin the recrudescence of seismic activity. This seismic activity is mostly concentrated in the South-Western part of the Basin where earthquakes are regularly felt. Three large earthquakes associated with foreshocks and long duration aftershocks mostly confined around the epicenter areas were already recorded in the Basin: The October 24th event with magnitude mb (6.1), the February event with magnitude mb (6,0) and the August 7, 2015 event with magnitude mb (5,8). Three events occurred at shallow depth around 10 km. It was observed small Tsunamis during these earthquakes reaching 5 m high and landslides on the shorelines near the epicenters. Many damages are regularly recorded in the villages and towns mostly near the epicenters area. Most of damages are correlated with the secondary faults which move when large earthquake occurred. More than 50 persons are already killed since 2002, by the earthquakes. The maximum intensity observed near the epicenter area is usually more than 8. According to the actual development of seismic activity, more large event is expected. The occurrence of such large earthquake may be catastrophe for the dense cities around the Lake Kivu basin in D.R. Congo and Rwanda side. The situation may be more catastrophe if it occurs inside the lake containing dissolved gas; carbon dioxide (CO_2) and methane (CH_4) in the deep water, with the possibility of gas explosion. This assertion is supported by the existence of active faults in this lake.
Keywords: Lake Kivu Basin, seismic, risk, faults, catastrophe.

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Seismic Microzonation and Site Effect Response of Al Auja District

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The town of Al-Aluja is one of the important Palestinian towns. The spatial distribution of the natural periods over a map is presented. It shows the important characteristics of soil deposit that will affect significantly the mitigation of the seismic risk impacts. The microtremors are very important and useful measurements in site response which could compensate the shortage and deficiency of the seismically recorded data, especially when there are missing seismic stations.
The aim of this study is to prepare a GIS-based microzonation map of Al-Aluja area for the purposes of urban planning theme. The predominant natural frequency at each site within Al-Aluja area was determined using the Horizontal to Vertical Noise Ratio (HVNR) of the microtremor records. It was applied to about 80 points which covered the whole studied area. Al-Aluja area was divided into cells by a grid system of 300 m x 300 m to estimate the effects of site conditions. The impedance contrast of soil deposit of sediments shows the distribution of frequencies and by using the outputs of these results, Al Aluja area is classified into four frequencies zones from 0.8 - 1.4, 1.4 - 2, 2 - 2.5 and 2.5 - 3.8 Hz. The results show that the lower bound estimate of amplification factor for a soil site is from 2 up to 18 times using microtremor peak values. And such of this study will use in seismic risk assessments and urban planning purposes in order to enhance the seismic design of the structure and implement some of the sound rules in natural disaster managements scenarios.

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Source effects of intraslab and interplate earthquakes off Miyagi Prefecture in Northeastern Japan and their relation to source depths

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Two different views have been presented as to the source effects (especially, the high-frequency level of acceleration spectrum) of intraslab and interplate earthquakes: (a) high-frequency level of intraslab earthquake is higher than that of interplate earthquake, and (b) high-frequency level depends simply on source depth, independent of tectonic environments, and high-frequency level is higher for deeper source. Kasatani and Kakehi (2014) (hereafter, KK) made spectral inversion analysis of the intraslab and interplate earthquakes off Miyagi Prefecture in Northeastern Japan using K-NET strong ground motion data of NIED. Their result supported (b). In this study, three events are selected from the events KK studied, and their strong ground motion data are analyzed. They are composed of two shallow events: S1 (intraslab, Mw 5.5, 35.94 km) and P (interplate, Mw 5.0, 42.86 km), and one deep event: S2 (intraslab, Mw 5.5, 83.10 km). In the comparison of attenuation relations of acceleration amplitudes, the slope of decay of deep S2 is obviously steeper than those of shallow S1 and P. On the other hand, in the spectral inversion of KK, common attenuation relation is assumed for all the events, independent of source depths. Actually, the attenuation relations of the acceleration amplitudes with the site effects (obtained in the spectral inversion) removed shows similar gentle slope of decay for all of the three events. This means that in the spectral inversion of KK, the strength of attenuation is underestimated for deeper events, and therefore, the high-frequency level of source is also underestimated for deeper events. When the steep decay of for deeper events are considered, high-frequency levels of deeper events will be higher than those obtained in KK, and the difference of high-frequency levels between shallow and deep events will become larger and more clear. This enhances the validity of the conclusion of KK that high-frequency level is higher for deeper source.

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Strong Ground Motion Simulation by Combining Stochastic Green's Function Method with Hybrid Slip Model for February 6, 2016 Meinong, Taiwan Earthquake

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A damage earthquake (Mw 6.53), which has struck the southern Taiwan, occurred in Meinong District of Kaohsiung City on February 6, 2016 (February 5 07:57:26.1 UTC). According to the relevant reports, many buildings collapsing during the seismic shakings were caused by local site effect in Tainan. To investigate the effect of shallow velocity structure on seismic ground motion, we calculate the broadband ground motions between 0.1-10 Hz by using the stochastic Green's function method. In this study, the velocity structures are established by integrating the crustal velocity structures and the near-surface velocity structures (0-1500 m) estimated from the microtremor array data. About the source model, we adopt a hybrid k-squared slip model with an asperity covering 1/4 of the fault area. The shallow velocity structures can well improve the synthetic results including amplitudes and phases and the directivity pulses are successfully reproduced at many stations. They indicate that the possible reasons for the earthquake disasters in Tainan are associated with a combination of forward-directivity and soil amplification effects. Thus, it is feasible to do the 1-D broadband strong motion simulations at the area using the stochastic Green's function method with hybrid k-squared slip distribution.

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Nonlinear Site Response During the 2016 Meinong, Taiwan Earthquake

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The Meinong earthquake occurred on February 6, 2016, at 03:57 (UTC+8) with ML 6.6. The epicenter was located in the Meinong district of Kaohsiung City, Taiwan, however, the highest intensity appears in the Tainan City. The strong ground motion induced soil liquefaction in the Sinshih and Annan districts of Tainan City. To investigate the nonlinear site response during Meinong mainshock, the degree of nonlinear site response (DNL) which summation of the horizontal to vertical spectral ratios (HVSR) differences between weak-motions and Meinong mainshock records from the TSMIP network is calculated. We compare the DNL values with the ground motion parameters such as PGA, PGV and also the ratio between PGV and VS30. The DNL show a positive correlation with ground motion intensity, particular with PGV, and the surface site conditions also leading the DNL strength. The areas that have high DNL values are consistent with the high potential liquefaction map that published by the Central Geological Survey, Taiwan.

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Evaluation of site effect by aftershock observation data due to the 2016 mid Tottori prefecture earthquake and microtremor observation in the mid area of Tottori Prefecture, Japan

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An earthquake (Mj6.6) occurred in central Tottori Prefecture in Japan on October 21, 2016. We conducted aftershock (strong motion) observation at several temporary sites in this area with housing damages. Also densely microtremor observations were carried out to estimate the characteristic of ground vibration in the damage area. Microtremor H/V spectra and a distribution of the predominant period were obtained from observation data. In addition, we checked the relationship between the site amplification effects and the results of analysis of strong motion and microtremor at the temporary observation sites. We found the characteristics of ground vibration form transfer functions of SH-wave by S-wave velocities, H/V of microtremor and receiver function and H/V of strong motion.

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The Probabilistic Seismic Hazard Assessment of South Africa

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More than 10 years has passed since previous national seismic hazard maps were prepared for South Africa. In those maps, zone-less techniques were applied. The availability of more reliable seismicity and geological data has made it possible to update those maps using probabilistic assessments that take into consideration all available data. Presented in this report, is a summary of the work conducted to produce the latest hazard maps for South Africa. This involved the systematic compilation and homogenisation of an earthquake catalogue, which comprised both historical and instrumental events.Work conducted in another project IGCP-601 to prepare a seismotectonic map of Africa, contributed much to the preparation of a corresponding seismotectonic map of southern Africa. The map consisted of major faults including possibly active faults in the region, focal mechanisms and seismicity. This information was also used in the preparation of seismic source zones for the hazard assessment. Two GMPEs were identified from available international models for regions that are tectonically similar to South Africa. These two models were then implemented in the hazard calculations, which were done using the OPENQUAKE software. Uncertainties associated with input parameters in both the seismic source and ground motion models were taken into account and implemented using the logic tree technique. Maps showing distribution of acceleration at three periods (PGA, 0.15s and 2.0s) computed for 10% probability of exceedance in 50 years were produced. The maps showed a strong influence of source zones associated with mining activity on the hazard of the country. The same mining regions were also observed to have the highest hazard. These maps constitute a valuable product of this study that can be useful in the mitigation of earthquake risks in South Africa especially considering the growth of its cities and also the location of major cities close to areas of high hazard.

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Generation conditions of long-period ground motions in the Kanto Basin

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In the Kanto (Tokyo) Basin in Japan, the long-period ground motion with period between 3 to 10 s are strongly developed when large (>M7) and shallow earthquakes occur nearby Tokyo. It is reported that the level of the long-period ground motion was very large from the earthquakes in Niigata but is several times weaker from the earthquake of Tohoku. In this study, we examined the cause of larger long-period ground motion in the Kanto Basin based on numerical simulation of seismic wave propagations. We first examined the directional amplification properties of the long-period ground motion in the Kanto Basin using a 3D heterogeneous sedimentary structure and a source model of the 2004 Niigata Chuetsu (Mw6.8) Earthquake. It is confirmed that the level of the long-period ground motion in Tokyo is strong when the source in Niigata, and is weak in Tohoku. However, it is insufficient to explain the large differences in the observation. Thus, we examined the source radiation effect of this event by modifying the strike of this source. It is found that the level of the long-period ground motion in central Tokyo is largely fluctuated with change in the strike of the fault, which had a largest when it corresponds to the case of the Niigata Chuetsu Earthquake. To examine the contribution of the surface wave propagation from the source to the Kanto Basin we conducted an another simulation with modified the free surface with a rigid boundary to suppress the surface wave propagation. As a result, the long-period motion in central Tokyo is dramatically weakened to about 1/2, indicating the importance of the surface wave propagation from the outside to the basin. The above results demonstrated that the strong long-period ground motion developed in the Kanto Basin during the Niigata Chuetsu earthquake was due to the fact that the surface wave is strongly radiated from the source to the direction to the Kanto Basin and that it can propagate well in the path to the Kanto Basin.

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Shallow to deep velocity structure modeling of Oita Plain, Japan, using microtoremor and borehole data

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Shallow to deep velocity structure around Oita Plain, Kyushu Island, Japan, has been modeled using data obtained by dense microtremor array survey and boreholes. Large aperture microtremor array surveys of their radius about 20 to 1000 m were deployed at 12 sites in the Oita Plain using T=10s velocity seismometers to estimate the phase velocity of the Rayleigh wave to constrain S-wave velocity down to the seismic bedrock. In addition, small aperture array surveys with radius less than 20 m were conducted at about 100 sites to constrain shallow S-wave velocity structure. About 3,000 borehole data comprised of soil types and SPT values are carefully interpreted to create 250 m mesh model of a layered soil structure (down to 100 m depth at most) composed of three significant layers. S-wave velocity structure of each mesh has been converted from the layered soil structure using an empirical equation among the N-value, depth, soil type and S-wave velocity. Synthetic dispersion curve of the phase velocity calculated with the S-wave velocity model agree well with the observed ones.

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Strong Ground-Motion Simulation of 2016 Meinong Earthquake Using Empirical Green's Function Method

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The Meinong Earthquake (ML 6.6) occurring at 03:57 local time (UTC+8) on February 6, 2016 has struck the southern part of Taiwan. It is very important to understand the characteristics of strong ground motions for the earthquake. Therefore, we simulate the ground motions of the Meinong mainshock using the empirical Green's function method. We first choose one small event to be the empirical Green's function (EGF) and select some CWBSN (Central Weather Bureau Seismic Network) stations surrounding the source area. Next, we calculate the averaged spectral ratios of the Meinong mainshock relative to the EGF records and then get the seismic moment ratio between these two events and their corner frequencies by the source spectral ratio fitting method. We further estimate two important parameters, the ratios of fault dimensions (N) and stress drops (C) between the Meinong mainshock and the EGF event, which are needed for the empirical Green's function method. Finally, we simulate the waveforms of the mainshock at all stations used and then get the best fit source model by comparing the synthetic waveforms with the observed data. According to the simulated results, the size of the strong motion generation area is about 55 square kilometers. The rupture started at the right-bottom of the strong motion generation area and extended radially to the left-upper direction.

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Segmentation of slow slip events in south central Alaska possibly controlled by a subducted oceanic plateau

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GPS data in south central Alaska show possible segmentation of slow slip behavior along the subduction zone. We hypothesize that the subducted Yakutat plateau created such segmentation through modification of stress or friction property of the fault zone. To test this hypothesis, we simulate the SSEs in the framework of rate and state friction. We use non-planar fault model to incorporate the geometric effect on SSE behavior. We also systematically explore the parameter space to find the most likely scenario and rule out some possibilities. The goal is to identify how such segmentation can be related to the subducted plateau in a physics model. Simulations show different effective normal stress could create such segmentation even though other mechanism exists. This is consistent with an idea that subducted plateau caused elevated effective normal stress in the fault zone, producing larger SSEs above it. The buoyant plateau provides additional normal stress on the fault interface, which results in larger SSEs in the east segment. Our results indicate that geological features have a long-lived impact on slip behavior of subduction faults. We also explored the interactions between the two SSE patches, as shown in the 2008-2013 slip events. Simulations show that the closeness of these two patches creates additional complexity in the behavior of SSEs.

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Difference in Ground Motion and Seismic Source Characteristics Between the Surface and Buried Rupture Crustal Earthquake in Japan

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Appearance of surface fault rupture in inland crustal earthquake affects significantly on ground motion characteristic. Somerville (2003) has indicated that the observed ground motion from buried ruptures are larger than those from surface rupture earthquakes in the period between range 0.3 and 3 sec. Following researchers explain the differences by fault rupture processes analysis using kinematic and dynamic source models of several part earthquakes (e.g. Kagawa et al., 2004). In Japan, inland crustal earthquakes have occurred frequently after the 1995 Kobe earthquake, and some of them had surface fault ruptures (e.g. 2016 Kumamoto earthquake). Yoshida et al.(2016) evaluated ground motion characteristics of the inland crustal earthquakes in Japan using the similar method as Somerville (2003). As a result, ground motions from buried rupture earthquakes are twice larger than those from surface rupture earthquakes in period range between 0.1 and 0.4 sec. We will report difference in the seismic source characteristics between the surface and buried rupture earthquakes using kinematic source models in Japan and discuss the difference of dominant period range between the result by Somerville (2003) and Yoshida et al.(2016).

Somerville(2003): Physics of the Earth and Planetary Interiors, 137, 201-212.
Kagawa(2004): Earth Planets Space, 56, 3-14.
Yoshida et al.(2016): Japan Geoscience Union Meeting 2016 Abstract, SCG061-P03.(in Japanese with English Abstract)

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Combining deterministic simulation of ground motions and probabilistic approach: Large scale simulation for heterogeneous source models by FDM reciprocity method

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Due to recent progress in velocity structure modelling, 3-D finite difference simulations have been proved to be accurate for simulation of long-period response spectra and waveforms. However, large scale simulations, e.g. for anticipated M9 Nankai Trough earthquake, are time consuming and become troublesome in case of probabilistic approach, which require simulation for many heterogeneous source models. Fortunately, for typical case in engineering seismology, namely for only one site that is hosting target structure of high importance (e.g. super high-rise building or long span suspension bridge) reciprocity method is an effective tool.

In this study we demonstrate effectiveness of reciprocity method. For this we use heterogeneous source modeling procedure of Sekiguchi et al., 2008. Generated ground motions can be studied in probabilistic way. For example, we can estimate effect of many heterogeneous source models, and find average, average plus standard deviation, or level of a certain probability of non-exceedance. In order to estimate average we may need to calculate 10 models, 30 models for average plus standard deviation and 100 models for 5% level of non-exceedance. We applied above methodology to study long-period ground motions in the Osaka sedimentary basin, Japan, from a hypothetical M9 earthquake in Nankai Trough. 100 source models having randomly generated slip, rupture velocity and location of SMGAs are prepared. Moreover, in order to account for variations of directivity effect, we generated ground motions for three cases of rupture start: in center and in west and east sides of model. Results show that in the deepest landward part of Osaka basin (site Konohana) the ground motions for periods 3-20sec are estimated to have peak velocities of 40–80cm/s, prolonged durations exceeding 300s, and long predominant periods of 5–10s; velocity response spectra for this periods are 190cm/s in average, and 290cm/s for average plus standard deviation.

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Maps of Volcanic and Seismic Hazards on the Web

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The MV SHOW it Project (Maps of Volcanic and Seismic Hazards On the Web) started in 2014 with the purpose to: (1) standardize 1:50,000 quadrangle scale hazard maps; and (2) make this information available online through the PHIVOLCS website. The project connotes a journey towards showing all available volcano- and earthquake-related hazards information online, servicing all its stakeholders in a more efficient way.

For the last two years, MV SHOW it has spearheaded standardization of hazard maps derived from the READY Project. It produced more than 800 images of 1:50,000 scale hazard maps.

In order to showcase hazards information on the web, it partnered with NAMRIA's (National Mapping and Resource Information Authority) Philippine Geoportal: One Nation One Map Project, and the Geological Society of Japan (GSJ). Partnership with NAMRIA resulted to the PHIVOLCS Geoportal and collaboration with GSJ made the progress of The PHIVOLCS Faultfinder possible. NAMRIA and GSJ developed the applications while PHIVOLCS manages, maintains and manipulates hazards information in its own server. Both applications utilize base maps provided by NAMRIA

The PHIVOLCS Geoportal app displays all available 1:50,000 scale earthquake-related and volcano-related hazard maps in the Philippines, as well as other geospatial information available in the Institute while the PHIVOLCS Faultfinder displays the distance of a user's location with respect to nearby active faults. Active faults shown in the application are results of various active fault mapping projects conducted by PHIVOLCS or in collaboration with international partners since the 1990s.

The MV SHOW it Project has also already started standardizing hazard maps in other relevant map scales, and has initiated ways to pro-actively engage its stakeholders through more user-friendly WebGIS and mobile applications.
Keywords: Philippines, earthquake, hazards, PHIVOLCS, webGIS, faultfinder, geoportal, MVSHOWit

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Characteristics of Seismic Response of the Taipei Basin

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The Taipei Metropolitan area is located on a triangular-shaped alluvium basin filled with the Quaternary unconsolidated sediments overlying the Tertiary basement. The sediments thicken northwestward from a thin basin margin in the southeast to about 700 m in the northwest corner of the basin. In order to investigate the characteristics of seismic response of the Taipei basin, the 5%-damped response spectral accelerations with periods, T, of 0.2 and 1 sec are calculated from the accelerograms recorded at the stations on the Taipei basin. The horizontal response spectra are calculated from the geometric mean of the spectral amplitudes of two horizontal components. Obviously, the spectral accelerations are higher in the Taipei basin than in the surrounding area due to the amplification of waves in the sedimentary basin. For the three Hualien offshore earthquakes, the maximum horizontal spectral accelerations are distributed near the eastern edge of the basin at T=0.2 sec and near the eastern and northern edges of the basin at T=1.0 sec. For two earthquakes occurred in central Taiwan, the maximum horizontal spectral accelerations at T=1.0 sec are distributed mainly near the eastern and western edges of the basin.

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Surface deformations caused by underground nuclear explosions

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We observed surface deformations at several sites within alluvial plain in the Semipalatinsk testing area. Field research included geomorphological observations and topogeodesic leveling along profiles with the length of 1,5-3 km. Technogenic forms of relief include:
-intensive ground loosening,
-ground swelling of amplitude from 0.5 to 1.0 m, length up to 20 m,
-local depression with a radies of 2 to 10 m, 0.5-0.7 m depth and
-ground fractures with a length of the first meters to 20 m and opening of 3-4 cm, rarely 10 cm.
We analyzed data that were carried on 20 objects before and after explosion and established that explosion caused deformation amplitude relates to the vertical peak ground velocity as a power function. Deformation area has a radius of 0.5 to 1.5 km. It is interesting that point of maximum deformation is displaced from the burst epicenter to the distance of 100-400 m.
The zonality of surface deformation corresponds to anthropogenic massif change due to the experiment and depends on massif lithologic-facial structure and physical-mechanical properties, underground water level, faults existence and paleorelief. In case of sedimentary and clastic rocks deformation area is asymmetric and corresponds to stratum attitude conditions. In tuffs it is usually uniform with the center at burst epicenter. In case of an explosion within shale and aleurolite massifs an elliptic cone is being formed along rock strike.
Shallow underground waters result increase of explosion impact on surface deformation. Maximum ground elevation without rupturing forms along the slope from terrace to flat due to soil displacement.
Large-scale experiments consequences corresponds to real post-seismic processes that were found out after earthquakes.
Described results are useful both for forecasting of areas of expected landslip processes and estimation of location and magnitude of historical earthquakes.
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Broadband Ground Motion along the Joetsu Shinkansen during the 2004 Chuetsu Earthquake and Aftershock Sequence

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During the 2004 Mw 6.6 Chuetsu earthquake, many aftershocks occurred following the main shock. In the main shock, the seismic intensity meter of Kawaguchi-cho in Niigata prefecture recorded seismic intensity level 7, and equivalent seismic intensity level 7 was observed at K-NET Ojiya of NIED and Shinkawaguchi electrical substation of JR East (ARAIC, 2007). Large seismic intensity was observed in the watershed of the Shinano river where was near the epicenter and has a complex velocity structure with large site amplification factors. During the 2004 Chuetsu earthquake, the first derailment of Shinkansen under operation ever occurred in which was slight south of the Nagaoka station of the Joetsu Shinkansen. The strong motion along the Joetsu Shinkansen has been discussed by Mori and Kazuni (2005), Nakamura (2006), and ARAIC (2007). Mori and Kazuni (2005) pointed out the influence of strong motion whose period was less than 0.5 second. On the other hand, the predominant period of the observed strong motion ranged from Ojiya to Nagaoka during the 2004 Chuetsu earthquake was 1 second. The 2004 Chuetsu earthquake and its aftershocks occurred in conjugated fault plane systems, both the hypocenter and velocity structures of which were complex. We here focus on the arrival times of P-wave and S-wave for the 2004 Chuetsu earthquake and the distribution of strong ground motions. We also discuss the strong motion of the 2004 Chuetsu earthquake along the Joetsu Shinkansen by conducting ground motion simulation of aftershocks with point-source assumption. We deal with seismic intensity meters such as Niigata prefecture, JMA, K-NET, and KiK-net, using earthquake source models from F-net and Hikima and Koketsu (2005). We use J-SHIS as the initial velocity structure model. We also conduct broadband ground motion simulation by using 3-D finite difference method and the stochastic Green's function method. Calculation results are compared with the ground motion prediction equation.

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Multi-use seismic stations for earthquake early warning

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Earthquake Early Warning (EEW) network performance improves with the number and density of sensing stations, quality of the sites and of strong-motion instrumentation, degree of coverage near at-risk populated areas and potential fault zones, and minimizing latency of signal processing and transmission. Seismic research tends to emphasize competing requirements: low-noise sites, high-performance broadband seismic instrumentation, and high-quality signal processing without regard for latency. Recent advances in instrumentation and processing techniques have made feasible the concept of a multi-use seismic station in which strong- and weak-motion seismometry are both cost-effectively served without compromising the performance demands of either.

Our concept for a multi-use seismic station meets the needs of both EEW and high-quality seismic research. One significant enabler is a 6-channel dual-sensor instrument that combines a 120s broadband seismometer and a class A accelerometer in a single ultra-compact sonde suitable for direct burial. Combining two sensors effectively adds broadband capability to a station without increasing the already optimized site footprint, preparation and management costs associated with shallow direct-burial installations. The combined sensors also simplify and speed up installation (for example, the accelerometer provides real-time tilt readings useful to leveling the seismometer). Integration simplifies alignment to north, as there is only one instrument to orient. A dual-use 6-channel digitizer simultaneously provides two sets of independently processed streams from both sensors, one set optimized for low-latency earthquake warning, and the other set for high-quality seismic research purposes.

Such a dual-use seismic station can serve both seismic research and civil warning infrastructure objectives without adding significantly to the cost of a single-use station, while increasing the utility for all users of the station's data.

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Studies on Qs of Kyushu district in Japan

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We have reported the variability of Qs in southern part of the Kyushu district, in the previous paper. In that paper, we used seismograms, which are from the M4-5 small-adequate scale earthquakes observed by K-NET and KiK-net operated by the National Research Institute for Earth Science and Disaster Resilience, for evaluating the Qs in those areas. As a result, it showed that the average apparent Qs of the line, connecting the seismic source location to the earthquake catalog of JMA and the observation point, changes significantly, depending on regions (route combination of propagations).

In this paper, we evaluate the Qs for the northern part of Kyushu, as the damping properties, using the twofold spectral ratio method and according the condition we assumed in previous papers. First, the northern part of the Kyushu district was divided into “Region A" and “Region B". In addition, the area in the southwestern part of the Kyushu district was indicated as “Region C". The evaluation of Qs was carried out in an area having a planar spread (Area), and as a propagation route (Line) respectively.

The results show clearly that different Qs are evaluated in Area-case and Line-case at each region, and also, Qs are very similar in “Region A" and “Region C". On the other hand, the Qs model of “Region B" which is very different from other regions agrees to the Qs estimated by Izutani (2000). He assumes the propagation path as just under Mt. Krishima. The Qs in other regions are harmonious with the ones estimated by Uchiyama and Yamamoto (2016).

Our results include only small number of earthquakes and the area to be analyzed, we have to continue the investigation for evaluating attenuation properties to perform the analysis, considering the variability of earthquakes and propagation path. As our future tasks, we plan to develop a method for evaluating complex damping structures in order to improve the accuracy of strong ground motion prediction.

Estimation of Empirical Green's Tensor Spatial Derivative Elements: A Preliminary Study using Strong Motion Records in Southern Fukui Prefecture, Japan

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In this report, I demonstrate the applicability of the EGTD method to simulate near-field strong-motion records for seven small events (MJ 3.7-4.2) that occurred in the southern part of Fukui Prefecture, Japan. Fukui Prefecture is an area with relatively low seismicity compared with other parts of Japan and strong motion data for EGTD estimation is less abundant. I targeted several nearby stations of the K-NET operated by the National Research Institute for Earth Science and Disaster Prevention (NIED). I performed EGTD inversion independently for each component for all time-sampling data. Using the estimated EGTD, I simulated the strong ground motion records for these events. The agreement between the observed and calculated waveforms for the all events is satisfactory over a long duration and there is a good match for the amplitude. The EGTD estimates in this report should be confirmed when future earthquakes occur around the same source area. This study targeted components lower than the corner frequencies of all events. Estimation of the broadband EGTD, including frequency ranges higher than corner frequencies, will be investigated in future work. I hope that this preliminary study in an area of relatively low seismicity is encouraging for the further investigation of EGTD estimation and evaluation of strong motion predictions using EGTD.

S-wave structure in the Nansei Islands, Japan, inferred from microtremor array explorations

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The Nansei Islands area of the southwestern part of Japan has often been damaged by large earthquakes and tsunamis. Strong-motion prediction for this area is so important for the disaster mitigation. The basic information for strong ground motion estimation is the subsurface velocity structure. Several seismic explorations have been carried out in the sea area around Nansei Islands to retrieve the P-wave velocity structure. However, few data of S-wave velocity structure for land part of these islands have been reported except our studies (e.g. Yamada and Takenaka, 2016). Although the J-SHIS model by NIED gives three-dimensional (3D) P- and S-wave velocity structures for the shallow part of the crust in the Nansei Islands as well as the other area in Japan, they have not been seismologically validated for this area, yet. In this study, we present the results of the microtremor array explorations at more than 40 sites in the Nansei Islands, where an S-wave velocity 1D model is given for each site. Based on them we could improve the J-SHIS model to construct a better 3D seismic velocity model. This velocity model could be used for seismic motion simulations of some actual earthquakes to check the validation of the model.

Effect of shallow S-wave velocity structure on ground motion characteristics at temporary aftershock observation stations of the 2016 Kumamoto earthquake

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Immediately after the 2016 Kumamoto earthquake, we have performed temporary strong motion observation for aftershocks of the event. Yamanaka et al. (2016) reported about this temporary observation and showed variety of the ground motions in the damaged areas in Kumamoto prefecture, Japan. It is observed that the stations where severe damage was observed shows larger ground motions than the less damaged areas. To understand the cause of variety in the ground motion characteristics, we have conducted microtremor array exploration at each temporary strong motion observation stations to reveal the S-wave velocity structure at near-surface. Chimoto et al. (2016) revealed that the low velocity layer at near-surface widely distributes in the damaged area from town of Mashiki to village of Minamiaso. This low velocity layer theoretically contributes to large amplification on ground motions. This study compares the ground motions observed due to aftershocks with the site amplification from shallow S-wave velocity structure. The spectral ratio was computed for site amplification characteristics calculated from the shallow S-wave velocity structures at each stations to that at the reference station as Yamanaka et al. (2016) did. Both spectral ratio for the observation and the calculation show peak at the period of about 0.2-0.3 seconds at most of the sites. However, large spectral ratio at the period around 0.5 sec. in observation was not observed in calculation especially at the heavy damage sites. This indicates the difference of deep structure which is not considered in this study. It is also investigated about the relationship between the average value of spectral ratio and AVS30. It is observed good correlation that large spectral ratio at the site with small AVS30. However, the value for observation shows larger value than calculation. This also indicates the large amplification may have been caused by not only shallow but also deep structure.

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SATREPS MarDiM Project on Earthquake and Tsunami Disaster Mitigation in the Marmara Region and Disaster Education in Turkey

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Since 1939, devastating earthquakes with magnitude greater than seven ruptured North Anatolian Fault (NAF) westward, starting from 1939 Erzincan (Ms=7.9) at the eastern Turkey and including the latest 1999 Izmit-Golcuk (Ms=7.4) and the Duzce (Ms=7.2) earthquakes in the eastern Marmara Region. The only un-ruptured segments of the NAF in the last century are within the Sea of Marmara, and are identified as a "seismic gap" zone.
Istanbul with high population similar to Tokyo in Japan, is located around the Sea of Marmara where severe damages expected to be generated as compound damages including Tsunami and liquefaction, when the next destructive Marmara Earthquake occurs. It was considered that Japanese and Turkish researchers can share their own experiences during past damaging earthquakes and can prepare for the future large earthquakes in cooperation with each other. Therefore, in 2013 the two countries, Japan and Turkey made an agreement to start a multidisciplinary research project, MarDiM SATREPS.
The Project is consisting of 4 research groups with the following goals.
1)"Earthquake Source region observational research". OBS, Electromagnetic and Seafloor extensometer observations has been conducted in order to identify the detailed seismic zone, fault geometry, 3D Velocity structure and reliable crustal deformation.
2)"Tsunami prediction based on earthquake cycle simulation research" focuses on scenario earthquakes and tsunamis occurrence along the NAF and precise tsunami simulation.
3)"Seismic characterization and damage prediction research" aims improvements and constructions of seismic characterizations and damage predictions based on observation researches and precise simulations.
4)"Disaster education using research result visuals from each research". Seminars with media representatives and local authorities have been organized in order to have effective dissemination of disaster information flow.

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The ground motion signature of supershear rupture in Burrdge-Andrews and free-surface-induced mechanisms

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There are two main mechanisms of supershear transition. One is usually called `the Burridge-Andrews mechanism' (BAM), on which a daughter crack nucleates ahead of the main crack tip by a high enough stress combining the peak shear stress moving at the shear wave speed developing ahead of the main crack tip (Andrews, 1976). The other one occurs on the free surface causing by the phase conversion of SV-P at the free surface (Kaneko and Lapusta, 2010; Xu et al., 2015), which we call `the free-surface-induced supershear' (FSI). Compared the rupture scenarios in BAM and FSI as shown, an evident different phenomenon is observed. That is, only one secondary supershear rupture front is nucleated in the in-plane direction in BAM whereas the secondary supershear rupture front is nucleated at the free surface in FSI. Besides, if the level of shear stress is high enough, both tow supershear rupture fronts are nucleated. These differences will finally results varying ground motion characteristics and radiation frequency contents. We perform systematic studies about this ground motion signatures of tow supershear mechanism. It will offer a practical tool to identify the supershear mechanism from the observation conversely and even the tectonic stress state since which cause different supershear mechanisms.

*S07-P-24
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S07. Strong ground motions and Earthquake hazard and risk

Observed Near-Fault Ground Motion Characteristics during the 2016 Kumamoto, Japan, Mainshock

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Strong motions of JMA seismic intensity of 7 were observed near the surface rupture at Mashiki town and Nishihara village during the 2016 Kumamoto, Japan, mainshock. We carefully integrated the observed acceleration records to velocities and displacements with correcting the base-line change in acceleration records, which would be caused by the effect of tilting of the seismometer. The corrected observations show large permanent displacements, which include near-fault terms. The amounts of permanent displacements coincide to geodetic observation results. We discuss those ground motion characteristics and compare those with other near-fault ground motion records.

*S07-P-25
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S07. Strong ground motions and Earthquake hazard and risk

Different spectra in the vertical seismic observation array

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We deployed the vertical seismic observation array in the Mizunami Underground Research Laboratory (MIU) constructed by Japan Atomic Energy Agency (JAEA). The vertical array consists of 4 seismic stations whose depths are 100, 200, 300, 400 meters, respectively. We installed 3 components accelerometer (JEP-6A3-10, Mitutoyo co.) in each station.
Although the seismic activity around MIU in the Tono region, Japan, is not high, some inland earthquakes occurred around MIU. We observed the seismic waves from these events in our vertical array. For an example, we observed the seismic waves from the event occurred at 21:10 JST on September 19, 2016. The JMA magnitude and the depth of this event are 3.0 and 7.3 km, respectively. The hypocentral distance between this event and MIU is about 30 km. The amplitude of the initial P wave at the shallow station is larger than the one at deeper station. We calculated the Fourier spectra of the direct P and S waves of these seismic waves. We found that the spectra in the 100-meter depth have more low-frequency (about 3 Hz) components than the ones in other depth. There is the geological boundary with the Mizunami group and Toki granite between 100 and 200-meter depth. We consider that the differences of the spectra in our array were caused by the geological boundary.
We have a plan of installing another seismic station to the stage 500 m in MIU (The depth of stage 500 m is 500 meters from the surface).

*S07-P-26
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground M
otion / S07. Strong ground motions and Earthquake hazard and risk

Surface wave propagation and magnitude (Mj) overestimates in western Japan

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It is recognized that the Mj of the Japan Meteorological Agency (JMA)'s scale sometimes shows large discrepancy between Mw. Typical examples were the Western Tottori earthquake in 2000 (Mj=7.3; Mw=6.7) and the Yamaguchi earthquake in 1997 (Mj=6.6; Mw=5.8), both are shallow, inland earthquakes in western Japan. Since the estimates of the Mj for shallow (h < 60 km) earthquake use the amplitude of the ground motion recorded by long-period (T0=5 s) seismometers, the propagation of the long-period ground motions might be different between northern and western Japan. In this study we examined the cause of such larger Mj by examining the long-period wave propagation from shallow inland earthquakes.

First we conducted regression analysis between Mj(from JMA catalog) and Mw(from GCMT catalog), for 47 inland earthquakes of shallow (h < 40 km) and large (Mj > 5.5) events occurred from Sep. 1994 to Nov. 2016 and obtained an equation of Mj = Mw + 0.16. We then selected the peculiar events which are largely deviated from the regression line, with larger Mj in Chugoku-Kinki area and a line area from south Fukushima to south Niigata, and smaller Mj in Tohoku area.

We then examined the strong motion record of the K-NET and KiK-net for the 2000 Western Tottori and the 2004 Mid Niigata earthquakes, and find that the attenuation of the long-period (5 s) ground displacement from the Mid Niigata earthquake is very strong with propagation in northern Japan, while very weak for the Western Tottori earthquake. Since the large ground motions appear in tangential motion, the observed large ground motion in western Japan is expected the fundamental-mode Love waves.
Therefore, the overestimates of the Mj in western Japan might occur due to the efficient development of the long-period (5 s) Love wave from shallow, strike-slip fault sources which propagates longer distances without significant attenuation and dispersion, probably due to the peculiarity of the shallow structure in that area.

*S08-1-01
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground M
otion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

Paleoseismological evaluation and surface faults of the 2016 Kumamoto earthquake along Futagawa fault zone, central Kyushu, Japan

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Futagawa fault zone was a main part of the source fault of the 2016 Kumamoto earthquake of Mj 7.3, which was the first case that a large earthquake accompanied with surface fault occurred on an active fault zone evaluated by the Earthquake Research Committee of Headquarters of the Earthquake Research Promotions (HERP). Therefore it is good opportunity to compare an evaluation before earthquake with surface faulting accompanied with the 2016 Kumamoto earthquake.

Futagawa fault zone is located in Kumamoto prefecture in Central Kyushu. HERP published Longterm evaluation of this fault zone in 2002 and 2013. Paleoseismological surveys were conducted by Kumamoto prefecture in 1995 and by AIST in 2007 and 2015. Paleoseismological trenching survey at Tanaka site by Kumamoto prefecture showed that the accumulated offset of sediments including AT volcanic ash (28 ka) was 5.2 m. They estimated average interval as 0.25 m/ka. And they also interpreted this offset was formed by 2 or 3 faulting events based on the observations of deformation of geological layers on the trench walls.

Maximum surface displacement accompanied with the 2016 earthquake along the Futagawa fault zone was ca. 2 m in the central part of this fault. It is consist with active fault evaluation by HERP. But amount of slip at Tanaka site caused by the 2016 Kumamoto eartquke was 0.5 m in the right-lateral component. Therefore amount of slip was over-estimate at this site, whereas recurrence of this fault was underestimated. If 0.5 m of displacement was recognized as a parameters of the characteristic deformation before occurrence of the 2016 Kumamoto earthquake, the recurrence interval would be rather short and probability of occurrence of earthquake would be rather high.

*S08-1-02
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground M
otion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

Paleoseismic history of the Hinagu fault zone, Kumamoto, Japan; Preliminary results of a trench excavation survey on the Takano-Shirahata segment

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We report preliminary results of the trench excavation survey of the Hinagu fault zone, one of the source faults of the 2016 Kumamoto Earthquake (Mw 7.0).
The Hinagu fault zone, striking NNE-SSW, is 81-km-long, strike-slip fault with dextral sense of shear accompanying vertical displacement. The fault zone is composed of three segments, Takano-Shirahata segment, Hinagu segment, and Yatsushiro Sea segment, from north to south (Headquarters for Earthquake Research Promotion, 2013). Associated with the 2016 Kumamoto earthquake series, approximately 6-km-long surface ruptures were produced by dextral strike-slip motion along the northern part of the Takano-Shirahata segment (Shirahama et al., 2016). We conducted paleoseismological investigations on the Takano-Shirahata segment, in order to estimate the future earthquake potential caused by each segments and the entire of the fault zone.
The Yamaide trench site is located on the middle part of the Takano-Shirahata segment. Soon after the 2016 Kumamoto Earthquake, we found slight tilting of the rice field surface and en echelon clacks at the southernmost part of the surface rupturing area, and we dug a trench across the ruptures. On the trench wall, fluvial sediments were observed and several obvious reverse faults cut them. The faults steeply dipped to the east and branched upward.
Based on the detailed observations for crosscutting relation between faults and sediments, we recognized several surface rupturing event horizons. The accumulative vertical displacements along the faults strongly support them. The results of radiocarbon dating showed that the three or four surface rupturing events after 15,000 yBP. In this presentation, we will report the seismic history of the Takano-Shirahata segment of the Hinagu fault zone revealed by the trench excavation survey, and discuss the relationship with paleoseismic histories of other segments.

*S08-1-03
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground M
otion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

Recent indications to improve evaluation of short active faults provided by the 2016 Kumamoto and Ibarakiken-hokubu, Japan, earthquakes

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Inland large earthquakes occur not only on major active faults but also in areas no active fault and/or minor short fault mapped. The number of potential destructive earthquakes of M˜7 estimated from the major active faults would be significantly underestimated. It leads a conservative evaluation that seismogenic fault up to ˜20 km is hidden or slightly truncated by the surface, and an M˜7 earthquake is assigned on each short fault. Based on field investigation and InSAR analysis for the 2016 Kumamoto earthquake, we here counter-argue that some of such minor and low-slip-rate faults might have been developed by insignificant but frequent slips triggered by nearby large earthquakes. Another implication to properly evaluate such short faults is provided by recent M˜6 class earthquakes at Ibaraki-ken-hokubu, in northern Kanto region, Japan. March 19, 2011 (Mj=6.1) and November 22, 2016 (Mj=6.3) Ibaraki-ken-hokubu earthquakes that might have shared a same short fault based on InSAR images and field survey. It enables us to interpret many short active faults might have been also developed by more frequent slip at only upper seismogenic layer due to M˜6 earthquakes.

*S08-1-04
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground M
otion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

Late Quaternary Faulting Along the Different Segments of the Philippine Fault in Mindanao Island, Philippines

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The Philippine fault is one of the most active tectonic structures in the western Pacific region that has generated at least 10 surface-rupturing earthquakes in the past 400 years. This sinistral strike-slip fault, with a length of about 1250 km, traverses the entire Philippine archipelago from northwestern Luzon in the north to eastern Mindanao Island in the south. Consisting of several segments, this arc-parallel and NNW-trending fault is related to the oblique subduction of the Philippine Sea plate beneath the archipelago.

In Mindanao Island, the Philippine fault traverses the eastern portion of the island for about 320 km. It is characterized by fault parallel ridges, systematic deflection of streams and fluvial terraces, sag ponds and tectonic scarps related to historical surface rupture. Based on tectonic geomorphic mapping using aerial photos and field surveys, the Philippine fault in Mindanao is divided into at least nine geometric segments separated by geometric discontinuities like dilatational steps and branching. In terms of its activity, at least two historical surface-rupturing earthquakes have been documented such as the 1879 M7.4 Surigao earthquake and the 1893 M7.3 Monkayo earthquake. Paleoseismic investigations conducted along the different segments in Mindanao also revealed multiple faulting events during the late Quaternary.

*S08-1-05
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otion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

Paleoseismology of the Himalayan Frontal Zones

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The damages of the April 25 2015 Gorkha earthquake aroused much concern about seismic risks along the Himalayan front though the rupture occurred only in a deeper part of the megathrust. 20 years of paleoseismological research have brought a lot of information on time and space of past earthquakes. However, we are still far from confidence on our ability to assess sesismic risks owing to the lack of information on both inter-plate and intra-plate earthquakes. From 2010 to 2014 within a JICA-JST SATREP* project in India, we have conducted paleoseismological studies on frontal and upper-plate faults at 7 sites. A few strike-slip faults in the upper plate were newly recognized and one of them, the Kangra Valley fault is supposed to be the source of the 1905 earthquake instead of the frontal fault. This indicates a possibly near future frontal earthquake in NW India. The last large event from the central seismic gap is still controversial, but one big event in 15 century or 1505 is being confirmed in one of our trenches. The next earthquake in the gap will be the most serious issue for India and Nepal. In order to know more about the future 1505 type earthquake, we need further studies in Nepal, where there is no consensus on the rupture sequence in space and time in the last millennium. (*Science and Technology Research Partnership for Sustainable Development by Japan International Cooperation Agency and Japan Science and Technology Agency)

*S08-2-01
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

Large earthquakes in historical and pre-historical times in Switzerland: An overview of earthquake induced effects

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During the last years, many studies have investigated pre-historical and historical earthquakes from traces left in sediments and the environment. The goal of this study is to gather and systematize available data potentially relevant for understanding seismic activity in Switzerland before the start of reliable historical records and to analyze it for the first time all together. The Earthquake Catalogue of Switzerland (ECOS-09) covers the period from 250 to 2009 AD and is only scarcely populated with events before 1100 AD. The new database extend back 0.5 Ma years, but is more rich in information for the time since 20'000 BP. Primary data for this new data collection come from recent paleoseismic studies and from studies from other disciplines (Sedimentology, archaeology, speleology, geomorphology and historical research) that focused on other goals, but include observations of potential relevance for understanding past strong ground shaking. Considering the combined data set, we identify 23 periods with an increased number of possible earthquake-induced effects. While all these effects could belong to various small earthquakes, or have a totally different, earthquake-independent origin, one admissible hypothesis we want to follow up in this study is also, to cluster these effects within time periods of increased number of observations, and to assign them to single earthquakes. For events after 1600 AD, highly reliable historical records are available, and earthquake induced effects can be assigned to known historical earthquakes. For the older period, eight events can be identified with paleoseismological evidence distributed over a wider area, possibly indicating a strong earthquake or a period of overall increased seismicity throughout Switzerland. The most prominent event occurred in the period 1900-2270 cal years BP. If assumed to be one single earthquake, it would be the strongest earthquake in the last 5'000 years in Switzerland.

*S08-2-02
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground M otion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

Application of the paleoseismic record of great Cascadia earthquakes for use in the 2015 and 2020 National Building Code of Canada seismic hazard maps

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The 2005 National Building Code of Canada (NBCC2005) used a deterministic model to derive the shaking from great Cascadia subduction interface earthquakes. The resultant values were used for design only if they exceeded the hazard values from other sources. NBCC2015 introduced a probabilistic treatment of Cascadia's Juan de Fuca segment. The rate of great earthquakes used the complete-rupture chronology established from turbidite analysis by Goldfinger et al. (2012 pre-print). Partial, southern ruptures were neglected as being too distant from Canada. The analysis used 18 turbidites of a 10,097-year record, giving a mean interval of 532 years and a standard deviation of 234 years. The rupture intervals (time since the last earthquake) were turned into magnitudes using fixed rupture length and width together with choices for slip rate and crustal rigidity to give central, upper and lower recurrence rates. Magnitudes were in the range 8.55-9.28. Three choices for the down-dip extent of the rupture were used, to capture the uncertainty in how close the energy release would be to sites on land. The model was combined with other crustal and inslab sources to give probabilistic seismic hazard estimates. The analysis neglected issues of partial rupturing and event clustering. Shaking from the offshore Cascadia subduction fault dominates 2015 design values in Victoria and Vancouver for periods > 1 s. For the NBCC2020 maps an updated turbidite history adds 4 events off Washington that decreases the mean interval to 434 years and reduces the standard deviation to 168 years, making the events appear more regular. The change in rate increases the onshore seismic hazard by about 9%.

*S08-2-03
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

The Great 1787 Earthquake (M 8.6) and Tsunami along the Mexican Subduction Zone – history, geology and tsunami hazard assessment

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The 1787 great earthquake (M 8.6) triggered a deadly tsunami that poured over the coast of Oaxaca, Guerrero, and Chiapas, along more than 500 km of the Mexican Pacific coast and up to 6 km inland. This tsunami, according with historical documents, destroyed mostly farmlands and livestock, and damaged few villages since the density of population was sparse at the time.

We report first on geological evidence from the Corralero lagoon and adjacent coastal plain that seem in agreement with historical accounts. The deposit left by the 1787 tsunami can be traced along a transect of cores and test pits from the coastline and up to 1.6 km inland. The test pits showed an anomalous sand layer that was deposited in a single event in the swales of a series of beach ridges. The anomalous layer is almost continuous along the transect, about a 1000 m-long, and is formed of coarse to medium sand, at variable depths up to 36 to 64 cm, with variable thickness, reaching about 28 cm and pinching up with the distance from the coastline. We used stratigraphy, grain size, microfossils (foraminifera and diatoms), magnetic susceptibility and anisotropy of magnetic susceptibility proxies to reveal the nature of this anomalous sand layer. Stratigraphy, abrupt contacts, and magnetic susceptibility support a sudden and rapid event, consisting of sands transported most probably by an extreme sea-wave far inland. Furthermore, based on the accounts of the 1787 earthquake (M 8.6) and tsunami, and estimates from Pb210 sedimentation rates, we suggest that this is the tsunami deposit left by the 1787 event. Tsunami modeling will further enhance the hazard and risk assessment of this area in Mexico.

*S08-2-04
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

Has the unusual “mega-tsunami" ever occurred along the Nankai Trough?

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Following the 2011 Tohoku-oki earthquake and tsunami, Japanese government reviewed their policies for earthquake and tsunami disaster management and mitigation measures. This review includes the idea of defining maximum magnitudes for earthquake and tsunami in the Nankai Trough subduction zone; M9 earthquake is supposed as the maximum possible class of earthquake in this area. However, at least in the eastern Nankai Trough region, this supposition does not concern the paleotsunami data such as tsunami inundation area reconstructed from the tsunami deposits. As a case study, we have researched the tsunami deposits by the excavation survey and reconstructed the Holocene tsunami inundation history in the Hamamatsu plain, facing the eastern Nankai Trough. Because of the progradation of the beach system during the last 7000 years, about 4 km seaward migration of the coastline has occurred in Hamamatsu plain. We reconstructed the location of the former coastlines based on the beach ridges, and estimated their ages by using the radiocarbon dating of the beach deposits. We found some tsunami sand layers intercalated in the inter beach ridge marsh deposits and determined their ages by radiocarbon dating method. Taking the location of contemporary coastline into account, we have not recognized the tsunami deposit suggesting an exceptionally large inundation area in the last 4000 years. It was found from the result that “mega-tsunamis" with much larger size than historical tsunamis have not occurred in this region at least in the last 4000 years.

*S08-2-05
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otion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

A large slip area of the 2011 Tohoku-oki earthquake has been already ruptured by the 1611 Keicho Tsunami earthquake (Mw9.0)

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The 1611 Keicho Tsunami earthquake generated huge tsunamis and caused a disaster along the Pacific coast of Tohoku area from Fukushima to Miyako. There are several historical documents, but some of them were controversial. Recently, Ebina and Imai (2012) checked historical documents in detail and made the most reliable data set of the tsunami inundation of the 1611 Keicho Tsunami. We compared the data set with the tsunami inundation of the 2011 Tohoku tsunami and found that the tsunami from the 1611 tsunami earthquake inundated larger distance than the 2011 Tohoku tsunami at many places.
The numerical tsunami inundation computations were carried out along the Pacific coast of Tohoku where reliable tsunami evidences of historical documents were available, such as tsunami evidence about 30 m height at Koyadori in Iwate or tsunami evidence at Suwa in the Sendai plain about 7 km away from the coast. Result indicates that the tsunami generated from the combination of two rectangular fault models, north fault with the length of 100 km, the width of 100 km, and the slip amount of 80 m and south fault with the length of 150km, the width of 100 km, and the slip amount of 40 m, explains all reliable evidences very well. The moment magnitude of the 1611 tsunami earthquake is calculated to be 9.0 by assuming that the rigidity is 3 x 10**11 N/m**2.
The northern part of the fault is located the north of the large slip area of the 2011 Tohoku-oki earthquake. The southern part of the fault, where 40 m slip was estimated, is located at the almost same area of the large slip area of the 2011 Tohoku-oki earthquake. This suggested that the 2011 Tohoku-oki earthquake re-ruptured the southern part of fault area ruptured by the 1611 Keicho tsunami earthquake. Because the plate convergence rate of Pacific plate along the Japan Trench is about 9 cm/year. A large slip of about 45 m estimated for the 2011 Tohoku-oki earthquake is similar to 36 m estimated from the convergence rate.

*S08-P-01
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otion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

Description and interpretation of the surface ruptures in northwest of the outer rim of the Aso caldera triggered by Kumamoto Earthquake

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Associated with the 2016 Kumamoto Earthquake, many surface ruptures were emerged in northwest area of the outer rim of the Aso caldera, which were located apart from the Futagawa and Hinagu Fault System, considered as the source fault of the earthquake, and rarely accompanied by seismicity. Overall distribution and deformation patterns of the surface ruptures in this area were shown by satellite radar interferometry analysis using ALOS-2 data, suggesting half-graben-like normal faulting triggered by north-south tensional stress field derived secondarily from the stress changes associated with the main source faulting (Fujiwara et. al. 2016, Morishita et. al. 2016). We carried out field surveys and identified characteristic surface ruptures at many places. Some of those have characteristics in shape that can be misread as surface earthquake faults. Recently such passive, or “accompanied" deformation of existing structure triggered by the change of stress field or seismic motion associated with earthquakes have been often reported since SAR interferometry has enabled the seamless and detailed understanding of surface deformation. These passive deformation might have occurred not specially for the reported events but universally in nature. Such passive deformation may be possibly included in the list of past surface earthquake faults and events recognized by trench surveys. We should start the discussion on the issue of reexamination of identification of characteristic earthquake events of active faults.

*S08-P-02
IASPEI Symposium / IASPEI02. Earthquake Hazard, Risk and Strong Ground Motion / S08. Paleoseismology and paleotsunami studies: their potential and limitation

Temporal clustering and occurrence probability of large earthquakes on active faults in Japan

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The 2016 Kumamoto earthquake (Mj 7.3) caused devastating damages and more than 180 casualties. It occurred in an active fault zone and surface ruptures appeared mostly along the previously mapped active faults (HERP, 2016). Meanwhile, the occurrence of large (greater than Mj 6.8) earthquakes on minor active faults has been more frequent in recent years. We here re-examined the frequency and probabilities of large earthquakes on active faults in the last 125 years, based on the historical catalogue of damaging earthquakes in Japan and previous reports. In total, 28 large damaging crustal earthquakes occurred in the last 125 years, and 22 of them (80 %) are related with mapped active faults, and 6 (20 %) are not. The 22 earthquakes in 125 years yield the average recurrence interval of 5.7 years. Using the individual recurrence intervals, 4.6+/-3.7 years is obtained for all damaging earthquakes and 6.0+/-5.5 years for those on active faults. The frequency distribution of recurrence intervals shows a bimodal distribution consisting of two groups. The average recurrence interval in the shorter group is 2.9+/-1.5 years. The longest interval is 17 years before the 1995 Kobe earthquake. It is thus apparent that the occurrence of the damaging earthquakes exhibits the temporal clustering and long quiescence periods. The temporal clustering is related with the occurrence of mega-thrust earthquakes such as the 2011 Tohoku earthquake, the 1944 Tonankai and 1946 Nankai earthquakes. Under the assumption of Poisson process, we obtained 72%, 92%, 100% probabilities within the next 5, 10 and 30 years for all damaging large earthquakes, and 62%, 86%, 99.7% for active fault earthquakes, respectively. If the present day is within a clustering period, the probability increases up to 68-97% within the next 5 years. To forecast them more accurately, the earthquake probability based on the BPT model for individual active faults and time-dependent seismic hazard assessment are necessary.

REFINEMENT OF PHILIPPINE TSUNAMI HAZARD MAPS: The TsuHaMEI Project

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The TsuHaMEI (Tsunami Hazard Map Enhancement using Interferometric Synthetic Aperture Radar (IfSAR)) Project of the Philippine Institute of Volcanology and Seismology (PHIVOLCS), initiated in 2016, aims to refine 1: 50,000 scale Philippine tsunami hazard maps, which were previously generated under the DOST-GIA Tsunami Project in 2007 and the READY Project from 2007 to 2013.

The TsuHaMEI Project finetunes tsunami inundation extent defined by previous projects by utilizing topographic contours extracted from 5m x 5m resolution 2013 IfSAR digital terrain model which has recently been available in the country. Resulting enhanced tsunami maps now indicate one-meter-interval tsunami wave height gradations, unlike previous maps which only showed generalized inundation areas. Maximum tsunami inundation distances and wave heights are adopted from previous results that used empirical and modelling techniques.

For the period 2016-2017, a total of 22 out of 67 tsunami prone provinces would have been completed. The maps are distributed to respective local government units for their use for local disaster mitigation and preparedness planning.

Keywords: Philippines, tsunami, TsuHaMEI, IfSAR, PHIVOLCS

*S09-1-01
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Round-the-world seismic echo effect in aftershock sequences of strong earthquakes: a statistical analysis

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The existence of the effect of the round-the-world seismic echo was shown in the work on a broad evidence base, including hundreds of the main shocks and thousands of aftershocks. The effect is that the surface waves excited in the earthquake source by the main shock makes a complete revolution around the Earth and excites strong aftershock in the epicentral area of the main shock. The physical nature of the effect is that a critical concentration of wave energy in epicenter is created by converging surface waves under achieving of epicentral area. Effect of the first seismic echo is manifested most clearly. Thus, in this report confirmed the hypothesis of the authors on the activation of rock failure under the cumulative impact of the round-the-world seismic echo onto the focal area unloading ("cooling off") after the main shock. Spatial patterns of effect manifestation and independence probability of its occurrence from the magnitude of the main shock were established. Theoretically predicted and experimentally observed phenomenon of the seismic echo can be used to improve the reliability of strong aftershocks forecast in determining the scenario of seismic process in the epicentral area of occurred a strong earthquake.
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Synchronization of Stick-Slip Oscillator by Periodic External Forces –Implications for Earthquake Activity Rhythms-

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Activities of small and large earthquakes and slow slip events (SSEs) have several rhythms, such as periodicity and seasonality, and earthquake recurrences on faults. They are caused by external forces such as tidal forces and interaction between fast or slow slips of earthquakes.

'Synchronization'is now recognized as a universal concept in nonlinear sciences. In this respect, I investigate responses of stick-slip oscillator to periodic external forces. In the numerical experiments, I examine stick-slip motions of a spring-slider pulling with a constant rate, where the friction following the laboratory-derived rate and state friction law is working on the contact surface between the block and the floor,
I found m:n synchronization, which is called as Devil's Staircase, when applying periodic external forces with the amplitudes of 1/10 and 1/100 relative to the stress changes in cycles. Synchronization occurs in cases of fe:fc(Tc:Te)=m:n (m and n are coprime integers) where fe(Te) and fc(Tc) are frequencies (periods) of external force and simulated system, respectively. In the non-synchronization cases, there appear some complex irregularities in the recurrence intervals with large fluctuations.

Earth and ocean tidal loading has stress with the amplitude of kPa-10kPa, and such loading may cause synchronization of SSE with small stress changes of several 100 kPa. Numerical experiments show a possible existence of repeating large long-term SSEs causing stress perturbation of MPa in the downdip of megathrust zone. My experiments indicate a possible synchronization of the megathrust recurrences. The recurrence intervals of large and megathrust earthquakes have some complex irregularity. These fluctuations may be caused by some complex non-synchronization effects between some adjacent fault segments.

Finally, we add some discussions on the viscoelastic cases where the elastic spring is replaced by a standard linear viscoelastic element.

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Synchronization and chaotic behavior of earthquake cycles in a model with interacting fault patches

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Numerical simulations are conducted to investigate the effect of interacting fault patches on complex earthquake cycles. In the model, circular patches of steady-state velocity-weakening frictional property are embedded on a planar fault in uniform elastic medium, and shear loading with a constant slip rate is applied to the fault. When a single isolated velocity-weakening patch exists on a fault plane, earthquakes repeatedly occur in the patch at a constant recurrence interval in usual cases. When two or three patches exist, earthquakes on the patches are synchronized with each other for cases where natural recurrence intervals of the patches are almost the same or close to integer multiple, resulting in single- or multi-periodic earthquake occurrence. In other cases, earthquake cycles tend to be chaotic, where the time intervals between successive earthquakes vary and no periodicity is found. Chaotic behavior of earthquake cycles is observed also for cases where slip in a velocity-weakening patch changes from seismic to aseismic. In these chaotic earthquake cycles, long-term forecast of earthquakes is impossible in strict sense. However, statistical property of earthquake recurrence can be used for probabilistic forecasts. An iteration map of the recurrence intervals of simulated earthquakes in chaotic pattern is expressed by a simple curve, indicating that the timing of an event is predictable from the previous time interval, and the sequence of slip events exhibits deterministic chaos.

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Observations and modeling of short-term phenomena in the preparatory stage of large earthquakes

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Past large earthquakes have ample but somewhat inconsistent short-term precursor reports. Utilising these information as prediction before a big event has proved to be formidably difficult. Meanwhile the data quantity has increased rapidly requiring high performance computers to analyse seismic or geodetic data. This trend has greatly contributed in understanding the details of how earthquakes rupture, but not very much on how they prepare themselves. We now know that slow slips contribute to stress re-distribution to complicate the matter.
We refer to a simple cellular automaton model of earthquake adopting Coulomb's failure criterion (Sacks and Rydelek, 1995) and incorporate the effect of dilatancy hardening. This numerical experiment reproduces Gutenberg-Richter's law, b-value decrease with tectonic stress increase and cut off of larger magnitude events after dilatancy hardening sets in. All these are observed in nature.
We speculate based on observations that fluid redistributions become evident when dilatancy breakdown starts to occur leading to triggering a large earthquake. Currently, this phase of the earthquake preparation process is not well established by observations, because they tend to appear sparsely and weakly. We review the Tokai area of the Nankai Trough where an M8 earthquake may be pending considering 1891 Nobi earthquake possibly affecting the sequence of >500 year historical recurrence of M8 events. We note that magnitude dependent seismic quiescence may be evident above the subjecting plate in Tokay area. This suggests that the ongoing preparatory stage is advancing involving a volume outside the plate subduction boundary where the eventual M8 may occur. We propose that the detection and understanding the current phase of preparation need to consider all possible models with physical plausibilities.

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Remote triggering of earthquakes as a possible stress-meter: the case of the 2016 M7.3 Kumamoto (Japan) mainshock

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Activation of seismicity at remote locations due to the passage of seismic waves from large earthquakes is well-documented. However, distant earthquake triggering is scarce in Japan, with the notable exception of the remote seismicity activated by the 2011 M9.0 Tohoku-oki earthquake. Here we report on a relatively widespread remote triggering of small events following the 2016 M7.3 Kumamoto earthquake and hypothesize on its causes.

We have processed waveform data recorded by high-sensitivity Hi-net and broadband F-net stations, operated by NIED, as well as JMA stations.

The activated seismicity correlates well with the passage of surface waves from the Kumamoto earthquake. The furthest triggered event was observed at Akan volcano (Hokkaido) at ~1630 km epicentral distance. Triggering has been also observed at other volcanoes in Tohoku, Chubu and around Izu Peninsula. Some active fault areas like Tottori and Noto Peninsula were also activated. The dynamic stresses at the triggered locations range from several to tens of kPa. Since most of the remotely triggered earthquakes were observed at volcanoes, the excitation of crustal fluids was likely the main triggering mechanism.

We found that the regions activated this time, in particular some volcanic areas in Tohoku, have been also activated after the 2011 Tohoku-oki earthquake. We hypothesize that mechanical weakening of a pressurized crust in these regions due to the 2011 megathrust might be responsible for an increased trigger-ability. In addition, the activation of some active crustal faults might be related to the levels of tectonic stress along these fault lines. These observations suggest that remote triggering might be used as a stress-meter at volcanoes and active faults.

Reference paper:
Enescu, B., Shimojo, K., Opris, A., and Y. Yagi, Remote triggering of seismicity at Japanese volcanoes following the 2016 M7.3 Kumamoto earthquake, Earth, Planets and Space, 68:165, doi:10.1186/s40623-016-0539-5, 2016.

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Coulomb Stress Transfer and Accumulation on the Sagaing Fault, Myanmar over the Past 110 years and Its Implications for Seismic Hazard

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The seismic hazard of Myanmar has attracted little attention from the world in the past. The economy and urban population of Myanmar is presently growing rapidly. In contrast, the buildings in big cities, such as Mandalay, Nay Pyi Taw and elsewhere, are poorly constructed. Therefore, many more people are now at risk from the earthquakes than before. So, the seismic hazard of Myanmar is drawing rapidly increasing attention from the world. The Sagaing Fault (SF), an active right-lateral strike-slip fault passing through Myanmar, has been being the source of serious seismic damage of the country. Thus, awareness of seismic hazard assessment of this region is of pivotal significance by taking into account the interaction and migration of earthquakes with respect to time and space. We investigated a seismic series comprising ten earthquakes with M>6.5 that occurred along the SF since 1906. The Coulomb failure stress (CFS) modeling exhibits significant interactions among the earthquakes. After the 1906 earthquake, 8 out of 9 earthquakes occurred in the positively stress-enhanced zone of the preceding earthquakes, verifying that the hypothesis of earthquake triggering is applicable on the SF. Moreover, we identified 3 visible positively stressed earthquake gaps on the central and southern SF, on which seismic hazard is increased.

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Testing the Coulomb stress triggering hypothesis for three recent megathrust earthquakes

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We test the static Coulomb stress triggering hypothesis for three recent megathrust earthquakes (the 2004 Sumatra-Andaman earthquake, the 2010 Maule earthquake, and the 2011 Tohoku-Oki earthquake) using focal mechanism solutions for actual earthquakes as receiver faults to calculate Coulomb stress changes. For the 2004 Sumatra-Andaman and 2011 Tohoku-Oki earthquakes, the median values of the Coulomb stress changes for 100 consecutive earthquakes revealed temporal changes from approximately zero before the megathrust earthquake to significant positive values following the mainshock, followed by a decay over time. Furthermore, the ratio of the number of positively to negatively stressed receiver faults increased after the megathrust. These results support the triggering hypothesis that the static stress changes imparted by megathrust earthquakes cause seismicity changes. This is in contrast to the results of a previous study that used optimally orientated receiver faults to calculate Coulomb stress changes, and this difference indicates the importance of considering the spatial and temporal heterogeneities of receiver fault distributions. For the 2010 Maule earthquake, however, the results are strongly dependent on fault-slip models. Since most receiver faults are concentrated in the mainshock source region, slip models significantly affect the computed Coulomb stress changes and sometimes cause anomalous stress concentrations along the edge of each sub-fault.

Fluid injection effects on induced seismic activity in multi-degree-of-freedom rate-and-state model

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The fluid injection influence on induced seismic activity was studied by numerical calculations of the peculiarities of motions of a system of blocks (consisted from up to 25 blocks) elastically connected with each other and linked by elastic springs to a constant-velocity moving driver (multi-degree-of-freedom spring-block model). The rate-and-state friction model with two-parametric friction law was adopted for description of the friction between the blocks and the substrate. Initially, the block system was in steady-sliding state, then its state was disturbed by the fluid injection and corresponding pore pressure increase. Influences of the model parameters (number of the blocks, the spring stiffness, velocity weakening parameter) on the process of the induced seismicity variations were considered.
It was shown that the considered spring-block system could exhibit different types of the motion patterns. The motion could be periodic or chaotic; the magnitude of the seismic events depends on fragmentation of the fault system (the number of blocks in considered model) and may have different values. The analysis shows, that the stiffness of link between the blocks affects significantly the behaviour of the model and resulting seismicity, so the main seismic activity could appear directly after the start of the fluid injection or in the post-injection phase. Different manifestations of the injection influence on the seismicity are observed also in the real cases. However, the parameters in the rate-and-state model are usually taken from laboratory experiments, and it is hard to believe that one should use the same values to describe the real scale phenomena. Yet our study showed, that it is possible to select more suitable parameters that will allow one to match results of calculations and data of real observations. It can be concluded, that considered model has the potential to be used for the estimations of the possible fluid-induced seismicity activity variations.

*S09-3-01
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Seismic valve as a driving mechanism of the 2014 aftershock sequences in West Bohemia

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The West Bohemia/Vogtland region is specific for its collocation of earthquake swarm activity and degassing of CO2 of mantle origin in a relatively small area. We present an analysis of three mainshock-aftershock sequences that occurred in May-August 2014 and was associated by fast increase of CO2 flow in a mofette, which reached six-fold of the original level during the subsequent 150 days. The following slow decay suggests that the seismic activity could have been driven by the fault-valve mechanism.
Our analysis of the spatiotemporal characteristics and focal mechanisms of the aftershock sequences shows that the three mainshocks occurred with unfavorably oriented mechanism in a step-over region of the fault plane with increased coulomb stress due to previous activity. The ETAS modeling shows that an additional aseismic source with an exponentially decaying strength was needed to trigger a large fraction of the aftershocks. Corresponding pore pressure simulations with an exponentially decreasing flow rate show a good agreement with the observed spatial migration of the aftershocks. We propose a scenario that the mainshock opened fluid pathways into the fault plane participating in the aftershock triggering. The migrating fluid pulse is then supposed to reach the surface and be observed as a long-term increase of CO2 flow rate in the mofette few days later.
We simulated gas flow in a two dimensional model of Earth crust composed of a sealing layer located in the hypocentre depth, which is penetrated with earthquake fault and releases fluid flow from a low-permeable lower crust to vertical high-permeable channel pointing to the surface. We get excellent and robust fit of the simulated flow to the data using a realistic vertical channel diffusivity showing that even this simple model is capable of explaining the observations including the short travel time of the flow pulse from 8 km depth to the surface, the following flow increase and later long-term decrease.

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A NEW APPROACH TO FAULT ZONE SEISMIC MONITORING

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The universal macroscopic parameter controlling the seismic efficiency of a slip on a fault is the shear stiffness or the rate of decreasing the resistance to shear during relative fault side displacement. An abrupt decrease of the fault shear stiffness, judging by the results of laboratory experiments, is caused by the presence of some minerals or watered clays in the fault principal slip zone. The decrease of stiffness inside a rock mass can be registered as an increase of the amplitudes of waves reflected from the fault zone, and thereafter as a decrease of the amplitudes of refracted waves.
Summarizing information about large-scale man-caused and tectonic earthquakes (structure of focal zones, triggering factors, mechanics of generation of different slip modes in faults, seismic efficiency, etc.) and methods of fault shear stiffness assessment allowed to elaborate a remote monitoring of potentially dangerous sections.
In order to test the measuring techniques and the principles of the observation system arrangement, measurements were set up in the pit of the "Korobkovskoe" deposit of ferruginous quartzites (Kursk Magnet Anomaly, Russia). Deformation and seismic measurements in the pit were held on two faults of different scales: the local one (about 50 cm thick) and the regional one (about 100 m thick). Relative displacements, accelerations and velocities of fault sides under the action of seismic waves produced by explosions in the quarry and in the pit were recorded. Durations of both disturbances were actually the same but the noticeable difference array reaction was noted on these two types of sources.
The change of waveforms caused by passage through a tectonic discontinuity was registered.
Records of the deformograph showed creep and slow events - abrupt changes of deformation character (failures) during which the deformation rate increases noticeably, but doesn't reach values intrinsic for normal earthquakes.

*S09-3-03
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Seismic sources under tensional regime - TRM and DEM approaches

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Seismic sources are most often modeled as shearing fracture processes (mode II and/or mode III fracturing) accompanied by complex frictional phenomena. Such approach has a solid support in field evidence for large natural earthquakes. Thus, the most of afford of describing seismic sources have concentrated on shearing-type models. However ,a situation is more complex
in case of anthropogenic siesmicity induced, for example, by mining. A large number of mining induced seismic events with significant volumetric (isotropic) component in the moment tensor solution have been reported suggesting that non shearing processes in seismic foci are not negligible. The sharing-like approach becomes even more problematic when micro-seismic events accompanying hydro-fracturing are concerned. In this case a tensional fracturing of reservoir rocks is highly desirable for engineering purpose and hydro-fracturing is design to meet this goal. However, in such a case to describe seismic/acoustic sources we cannot further on use a formalism developed for shearing-like sources – including tensional rupture mechanisms (mode I fracturing) is absolutely necessary.

In this presentation we discuss two different approaches to modeling non-shearing seismic/acoustic sources under tensional regime based on two well developed approaches. The first one, is based on the time reversal imaging (TRM) of acoustic sources. The second approach relies on a direct ``brute-force'' simulations of material fragmentations based on the discrete element method (DEM).

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Estimating the Locations of Past and Future Large Earthquake Ruptures in California using Recent M4 and Greater Events

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Although most aftershock activity dies away within months or a few years of a mainshock, there is evidence that aftershocks still occur decades or even centuries after mainshocks, particularly in areas of low background seismicity such as stable continental regions. There also is evidence of long-lasting aftershock sequences in California. New work to study the occurrences of recent M4 and greater earthquakes in California shows that these events occur preferentially at the edges of past major ruptures, with the effect lessening with decreasing magnitude below M4. Prior to several California mainshocks, the M4 and greater seismicity was uniformly spread along the future fault ruptures without concentrations at the fault ends. On these faults, the rates of the M4 and greater earthquakes prior to the mainshocks were much greater than the rates of the recent M4 and greater earthquakes. These results suggest that the spatial patterns and rates of M4 and greater earthquakes may help identify which faults are most prone to rupturing in the near future. Using this idea, speculation on which faults in California may be the next ones to experience major earthquakes is presented. The results of these analyses also indicate that the locations of recent M4 and greater earthquakes may be useful for determining the spatial extents of historic and paleoseismic earthquake ruptures.

*S09-3-05
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CSEP-Japan earthquake predictability experiment for physics-based modeling and testing

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It is 6 years since we have established the Japanese testing center for the Study of Earthquake Predictability (CSEP) in Earthquake Research Institute, the University of Tokyo. During the period of testing, in March 2011, Tohoku-oki earthquake with M9.0 occurred. The testing experiment consists of 12 categories, with 4 testing classes with different periods (1 day, 3 months, 1 year and 3 years) and 3 testing regions called "AllJapan," "Mainland," and "Kanto." A total of more than 160 models are currently under testing in the CSEP Japan official suite. For three-month and one-year testing experiments, more than 30 runs of fully prospective experiments have been completed and evaluated.

After the 2011 Tohoku-oki event, most models show poor N-test performance due to large effects of the event. We found that the performance is improved if the effects were modeled explicitly by Omori-Utsu formula. The direct effect of the 2011 event needs to consider a post-seismic slip on the source fault and viscoelastic relaxation of the M9 event in the crust and the mantle.

*S09-P-01
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The relation between the deep lithospheric structure and observed seismicity in the European Arctic

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Installation of new seismic stations on Franz Josef Land allows us to use also weak earthquakes to refine the seismicity of the European Arctic (mb 0.9-6.6, representative magnitude 2.9, assumed location uncertainty 5-10 km). The new data are used as the base for studying the geodynamics of the area i.e., to investigate the relation between the lithospheric structure and seismic activity. Profiles of lithospheric structure were taken from published DSS data. One long north-south profile intersects the Gakkel Ridge, the Nansen Basin, the Barents shelf, part of the Fennoscandian shield, the White Sea and the continental uplift of the East European platform. One long west-east profile intersects the Svalbard anticline, the North Barents Basin, the North Kara Basin and the Taimyr-North-Zemaljskaya fold systems.
The correlation of the earthquake spatial distribution with the lithosphere structure of the European Arctic region was studied and the agreement of seismicity with different morphological structures was shown. A new approach was applied to identify zones with different seismicity. It is based on the events grouping on grounds of similar spectra. For this, spectral-temporal analysis of earthquakes was performed. By the spectra we observed a clear distinction of earthquakes occurring at the junction of continental and oceanic lithosphere from earthquakes occurring at the Graben Franz-Victoria and falling in the ruptured zone. There are two groups of events on the Gakkel Ridge, associated, probably, with volcanic and tectonic processes. Also two groups of events were defined on the shelf, which are representing the different tectonic structures of the South-Barents depression and Novaya Zemlya Foreland Basin.
Our study allows for the first time to propose a geodynamic zoning of the lithosphere in the European Arctic. This result is important for seismic hazard studies in the region, in particular in the case of future industrial development of the offshore areas.

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Postseismic Process of Moderate and Large Interplate Earthquakes within the Source Area of the Megathrust Earthquakes Along the Nankai Trough

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Recent two M6˜7-class earthquakes occurred within the source area of great interplate earthquakes nearby the Japanese Islands were followed by contracting consequences: the 2016 Kumano-nada earthquake above wasn't followed by the great interplate earthquake, while an M7-class interplate earthquake which occurred at off-Tohoku region in March 9, 2011 was followed by the 2011 Tohoku-oki earthquake, and was regarded as one of the foreshocks of the off-Tohoku earthquake. Such different consequences are probably caused by the different preparation level of the great interplate earthquake at the timings of occurrences of these M6˜7-class earthquakes. When the occurrence of great earthquake is approaching, postseismic slips after the M6˜7-class earthquakes can easily propagate to the surrounding region and can trigger the subsequent great event. While, if the fault is not urgent to the great event, strong coupling on the fault may prevent postseismic slip from propagating to the surrounding area. These differences in postseismic slip patterns strongly affect the corresponding crustal deformation. Hence, from occurrence pattern of the crustal deformation after the M6-7 earthquake in the target source region, it might be possible to narrow down the subsequent scenarios that can occur. In this study, we focus on the Nankai Trough region, and firstly examine the possible propagation pattern of afterslips of the hypothetical occurrence of earthquakes such as M7-class Hyuga-nanda earthquake or M6-class Off-Kumano earthquake in many Nankai Trough earthquake scenarios deduced from numerical simulations. Then, we classify the expected postseismic deformation patterns depending on the propagation patterns of particular afterslip. In order to evaluate realistic crustal deformation, we will evaluate crustal deformation associated afterslips not only in a homogeneous elastic half-space but also in FE models with heterogeneous crustal structure and the configuration of bathymetry.

*S09-P-03
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Time to instability of the seismic event triggered by SSE

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At the subduction zone along the Nankai Trough, SW Japan, large earthquakes around M8 had repeatedly occurred. The existence of short-term large aseismic processes at the deeper extension of the seismogenic region before the 1944/46 events has been inferred (e.g. Linde and Sacks, 2002).
We showed that such preseismic process could occur in 2D earthquake cycle models controlled by the friction with intrinsic cut-off time for healing (Ohtani et al., 2016). In the simulated cycles, large slow slip events (SSEs) occurred at the deeper extension of the seismogenic zone, and sometimes triggered the earthquake. We systematically investigated over a range of model parameters and found that the time between an earthquake and the most recent SSE, tf, fell into two separate classes; within 38.4 days or over 7.7 years. The former represented SSE-triggered earthquakes, and tf takes a few days on average. Given that the timing of SSEs is probably not affected by the failure condition of the seismogenic part, the observed concentration of tf to small values seems to be unexpectedly strong.
In order to understand the result, we here investigate the slip response to the stress perturbation in a 1D spring-slider model with RSF friction. To model SSE-triggering in the 1D system, we move the load point at the velocity (1−r)Vpl, and give the step Δu=rVplTr_load every Tr_load=34 years. The slider produces periodic unstable slip with a recurrence interval of Tr=102 years, that is, an earthquake occurs after third SSE. Then, we impose the third SSE at a random timing T0 to synthesize the statistics of tf.
For larger SSE, tf concentrates more strongly to smaller values. We calculated the cumulative probability that earthquake occured by tf. Even in a case of large SSE (r=0.9), 50% of earthquakes required tf>0.36 years. It seems that the strong concentration of tf observed in the 2D model is not simply explained by the delayed (RSF) failure mechanism represented in 1D model.

*S10-1-01
IASPEI Symposium / IASPEI03. Earthquake Generation Process / S10. Develop
ment, testing and application of earthquake forecasting models

Prospective evaluation of the CSEP-Japan earthquake forecasts experiments

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Collaboratory for the Study of Earthquake Predictability (CSEP) is a global project of earthquake predictability research. The primary purposes of the CSEP is to develop a virtual, distributed laboratory. The final goal of this project is to investigate the intrinsic predictability of earthquake rupture mechanisms.

A total of 160 models were submitted from all over the world to Japan Testing Center. CSEP-Japan keeps the prospective experiments from 1 November 2009. The models are currently under test in 12 categories, with 3 testing regions and 4 testing classes of different time spans (1day, 3 month, 1 year and 3 years). We evaluate the performance of the models in the official suite of tests defined by the CSEP (L, M, N, S) against authorized catalogue compiled by Japan Meteorological Agency. In addition, we investigate the model performance using log likelihood and information gain per event.

CSEP-Japan testing center has conducted over 30 rounds tests for 3-month testing classes including 2011 Tohoku-oki earthquake. We will discuss these results of evaluation test of the prospective experiments, and checked and compared the performance of the earthquake models.

*S10-1-02
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Using GNSS data to analysis the earthquake potential of Sichuan-Yunnan region, western China

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We used GNSS data to estimate the seismic hazard potential in the Sichuan-Yunnan region, western China by two approaches.
The first approach, based on the assumption that the earthquake probability is proportional to crustal strain rate, is to use secular geodetic strain rate deduced from GPS velocity data to constrain the probability model. Retrospective test of the model with earthquake occurrence of the past 30 years shows that the model 'forecasted' poorly. However, the model seems to 'forecast' spatial intensity of earthquakes for the past 500 years reasonably well, suggesting that the geodetic strain rate obtained at the decadal scale may still be a good indicator of long term earthquake activity in the region, but only at a time scale of hundreds of years.
The second approach is to use GPS velocity data to determine the seismic moment accumulation rates on major faults, and use a historical earthquake catalog to estimate seismic moments released in the past. Comparison of the two yields estimates of present day seismic moments accumulated on major faults, and a retrospective test shows some predictive power of the method.
Our result shows that numerous faults in the Sichuan-Yunnan region have accumulated seismic moments capable of producing M > 7.5 earthquakes, which are the Xiaojiang, Jiali, Northern Nujiang, Nandinghe, Red River-Puer faults, and the junction fault between the Xianshuihe and Ganzi-Yushu faults.

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Seismological and geodetic tools can jointly contribute to the understanding and prediction of earthquakes

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Earthquakes cannot be predicted with precision but, based on seismicity patterns, algorithms exist for intermediate-term middle range prediction of strong main shocks. A first attempt was made in the framework of project SISMA funded by Italian Space Agency to jointly use seismological tools, like CN algorithm and scenario earthquakes, and geodetic methods and techniques, like GPS and SAR, to constrain priority areas where to concentrate prevention and seismic risk mitigation.

Here the seismic crisis, started in Central Italy in August 2016 with the Amatrice earthquake is considered in a retrospective analysis of both SAR and GPS data, including stability tests.

Differently from the common approach, GPS data are not used to estimate the standard 2D velocity and strain field in the area, but to reconstruct the velocity and strain pattern along transects, properly oriented according to the known tectonic setting. SAR data related to the Amatrice earthquake coseismic displacement are used as independent check of the GPS results.

This further development of integration of seismological and geodetic information, clearly shows the contribution of geodesy to the understanding and prediction of earthquakes. In fact, it turns out possible to highlight the velocity variation and the related strain accumulation in the area of Amatrice event, within the area alarmed by CN since November 1st, 2012. Some counter examples, across CN alarmed and not-alarmed areas, do not show any spatial acceleration localized trend, comparable to the one well defined along the Amatrice transect.

The combined analysis of the results of intermediate term middle range earthquake prediction algorithms, like CN, with those from the processing of adequately dense and permanent GNSS network data, possibly complemented by a continuous InSAR tracking, may allow the routine highlight in advance of the strain accumulation. Thus it is possible to significantly reduce the size of the CN alarmed areas.

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On what time scales can strain rates contribute to earthquake likelihood models?

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Recently a multiplicative modelling technique was developed for combining earthquake likelihood models and gridded covariates into hybrid earthquake likelihood models. Multiplicative hybrids often have larger information gains than additive hybrids produced from the same inputs. We have applied the technique to evaluate the information gains from incorporating strain rate maps into existing earthquake likelihood models on two timescales.
In a long timescale study, we use three components of the strain rate in New Zealand estimated over the period 1991-2011 – the shear (SSR), rotational (RSR) and dilatational strain rate (DSR). We fit multiplicative hybrid models using selections of covariates, constructed from earthquake catalogue and fault data as well as the strain rate components, to the period 1987-2006 and test them over the period 2012-2016. The SSR provides the greatest single information gains in forecasting M 5 and greater earthquakes in the fitting and testing periods. Most models including strain rates are more informative than the best models excluding strain rates. A hybrid that combines SSR and DSR with a smoothed seismicity covariate is the most informative in the fitting period, and a simpler hybrid without DSR is the most informative in the testing period.
In a short timescale study, we use daily estimates of strain rate on the shallow Hikurangi subduction megathrust as a multiplicative covariate. We average daily strain rates over four time windows (1 day, 30 days, 100 days, and 460 days) to test the link between duration of strain and triggered earthquakes of magnitude 3.5 and greater in subsequent time windows of the same length. We find that the 30-day window provides the largest information gain, followed by the 460-day window. These results may be related to the rapid triggering of earthquakes during slow slip events (SSE). Shallow SSE have typical durations of weeks and deep SSE have typical durations ranging from months to over a year.

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Reducing false alarms of annual forecast in the central China north-south seismic belt by reverse tracing of precursors (RTP)

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The annual consultation on the likelihood of earthquakes in the next year, the ‘Annual Consultation Meeting', has been one of the most important forward forecast experiments organized by the China Earthquake Administration (CEA) since the 1970s. In such a consultation meeting, annual alarm regions are identified by an expert panel considering multi-disciplinary ‘anomalies'. One of the problems in need of further technical solution is its false-alarms. To tackle this problem, the concept of ‘reverse tracing of precursors (RTP)' proposed by Keilis-Borok is used to the annual consultation. The central China north-south seismic belt (in connection to the CSEP testing region) is selected as the testing region of such an approach. Applying the concept of RTP, for an annual alarm region delineated by the Annual Consultation Meeting, the distribution of ‘hotspots' mapped by the pattern informatics (PI) algorithm, which targets at the five-year-scale seismic hazard, is considered. The ‘hit', or successful forecast, of the annual seismic hazard, is shown to be related to sufficient coverage of the ‘hotspots' within the annual alarm region. The ratio of the areas of the ‘hotspots' over the whole area of the annual alarm region is thus used to identify the false-alarms which have few ‘hotspots'. The results of the year 2004 to 2012 show that using a threshold 17% can reduce 13 among 38 of the false-alarms without losing the successful hit (being 6 in that period).

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Break of slope in earthquake size distribution and aseismic deformation rate

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Crustal faults accommodate slip either by a succession of earthquakes or continuous slip, and in most instances, both these seismic and aseismic processes coexist. Recorded seismicity and geodetic measurements are therefore two complementary data sets that together document ongoing deformation along active tectonic structures. We show that creep along the San Andreas Fault is responsible for a break of slope in the earthquake size distribution. This slope increases with an increasing creep rate for larger magnitude ranges, whereas it shows no systematic dependence on creep rate for smaller magnitude ranges. This is interpreted as a deficit of large events under conditions of faster creep where seismic ruptures are less likely to propagate. These results suggest that the earthquake size distribution does not only depend on the level of stress but also on the type of deformation.
Significant part of postseismic deformations is known to be aseismic, and the aftershock process consists of both seismic events and aseismic relaxation of stress. Accordingly, we suppose that magnitude-frequency relation for aftershocks may experience a break of slope. We test this hypothesis on the example of several aftershock sequences of major earthquakes and show that in most cases a two-slopes model statistically is preferable. The practical issue is that forecasting models of aftershocks, hypothesizing a single-slope magnitude distribution of earthquakes, may significantly overstate (or sometimes understate) the expected rates of large aftershocks. We demonstrate it on examples. The research was partially supported by Russian Science Foundation (Project N 16-17-00093).

*S10-P-02
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Application of earthquake forecasting models in central New Zealand following the November 2016 Kaikoura earthquake

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Following the M7.8 Kaikoura earthquake of 14 November 2016, GNS Science, through the GeoNet website, provided forecasts of future earthquake occurrence, similar to the practice that has evolved during major earthquake sequences in New Zealand since 2011. The forecasts were expressed in three forms: (1) Tables of the number of earthquakes expected during future time periods in different magnitude ranges within a defined aftershock region, with associated uncertainties; (2) Maps of the probability of earthquake shaking exceeding certain Modified Mercalli intensities; and (3) Future earthquake scenarios with associated probabilities. Initially the short-term earthquake probabilities (STEP) model was used to estimate the expected number of earthquakes of magnitude 5.0 and above for time periods of 1, 7 and 30 days. A week after the mainshock, the 1-day forecasts were discontinued and yearly forecasts were added. After five weeks, only monthly and yearly forecasts were produced. The latter were based on a hybrid model, with long-term, medium-term and short-term components derived from well-established models. The long-term component was provided by a smoothed seismicity model, the medium-term component by two versions of the Every Earthquake a Precursor According to Scale (EEPAS) model, and the short-term component by the STEP and Epidemic-Type Aftershock (ETAS) models. The Kaikoura earthquake presented some particular challenges: (1) Careful communication of changes to the estimated mainshock magnitude, the contributing models and the method for estimating uncertainties in the expected number of earthquakes (a switch from the Poisson to the negative binomial distribution); and (2) Amendment of forecasts to allow for increased slow slip on the North Island subduction interface after the Kaikoura earthquake. In the absence of any established models to incorporate slow slip into the forecasts, the probability of a triggered major event was assessed by expert elicitation.

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Time-dependent neo-deterministic seismic hazard scenarios for the Italian territory: recent advances and testing issues

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Long-lasting practice and results obtained for the Italian territory in about two decades of rigorous prospective testing of CN and M8S algorithms, support feasibility of earthquake forecasting based on the analysis of seismicity patterns at the intermediate-term middle-range scale. The algorithms permit to deal with multiple sets of seismic transients and allow to identify the region and time interval where a strong event is likely to occur. Based on routinely updated space-time information provided by CN and M8S forecasts, an integrated procedure has been developed for the definition of time-dependent seismic hazard scenarios through realistic modeling of ground motion by the neo-deterministic seismic hazard assessment (NDSHA) approach. This scenario-based methodology permits to construct, both at regional and local scale, actual scenarios of ground motion at the times when a strong event is likely to occur within the alerted areas.
Recent advances and results from real-time testing of the integrated NDSHA scenarios are illustrated, with special emphasis on the sequence of destructive earthquakes in Central Italy starting on 24 August 2016. Some basic operational and testing issues are addressed, ranging from testing homogeneity/reliability of the input data to the adequate assessment of output information. The results obtained so far support the validity of the proposed methodology in anticipating ground shaking from imminent strong earthquakes and show that the information provided by time-dependent NDSHA can be useful in assigning priorities for timely and effective mitigation actions.

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TEC anomalies immediately before large earthquakes: Review and perspective

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Heki (2011) found ionospheric total electron content (TEC) enhancement starting ~40 min before the 2011 Mw9.0 Tohoku-oki earthquake. Heki & Enomoto (2015) confirmed similar phenomena before all the earthquakes in this century with Mw 8.5 or more. Critical papers claim that (1) the preseismic increase is an artifact popped up by defining the reference curves using the data after earthquakes, and (2) the anomalies originate from geomagnetic activities rather than earthquakes. In our rebuttals (Heki & Enomoto, 2013; 2014; 2015), we demonstrated statistical significance of the preseismic increases of vertical TEC rates. We also counted the occurrences of similar changes in TEC caused by space weather during times of no earthquakes and demonstrated it statistically unrealistic to attribute all the preseismic anomalies to space weather.
Recently, He and Heki (2016) analyzed the spatial distribution of preseismic TEC anomalies of 3 large earthquakes in Chile, i.e. the 2010 Maule, the 2014 Iquique, and the 2015 Illapel events. There, both positive and negative anomalies started simultaneously at altitudes of ~200 km and ~400 km, respectively, with 3-D structure similar to Kuo et al. (2014) predicted as the ionospheric response to positive electric charges on the ground.
We found three different Mw dependences of the anomalies so far. At first, the amount of the preseismic TEC rate changes are stronger for larger earthquakes and under higher background TEC. Secondly, larger earthquakes tend to have longer precursor times. Third, the anomalies of larger earthquakes have larger spatial dimensions. In the latest work, He and Heki (submitted) studied 32 earthquakes with Mw7.0-8.0 in this century, and found that 8 earthquakes showed possible preseismic changes starting 20-10 minutes before earthquakes. We could observe them before Mw7.0-8.0 earthquakes when background VTEC are large, say over 50 TECU.

Modification of ionosphere before March 11 2011 Tohoku earthquake

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Ionosphere disturbance which was seen prior to an earthquake which occurred on 11 March2011 off the coast of Tohoku was studied. Ionosphere data which were used are: O+ density acquired with US satellite DMSP, and NmF2, and h'F obtained by ionosondes. Global Ionosphere Model (GIM) is used as side evidence to compliment findings from DMSP data and ground based data..
Although during the earthquake preparation period, magnetic disturbance is strong, global survey of ground based foF2 shows that special disturbance is limited to earthquake area. Satellite data(DMSP and GIM) analysis shows three important findings before the occurrence of the earthquake; (1) Over geomagnetic equator enhancement of O+ is found, (2) midlatitude trough is formed before the earthquake and it moves toward lower latitude as EQ day approaches, and (3) no clear difference of O+ behavior between east and west of the epicenter is identified. Night time NmF2 at high latitude ionosonde stations such as Khavalovsk, and Beijin shows 2 days oscillation from 5 March and disappears on the 12th March. As the latitude of the station is lower, 2 days oscillation becomes unclear, and the duration of the appearance is shorter.
In order to explain both ground based and satellite data consistently, one idea of enhanced east/west ward dynamo electric field during daytime/ nighttime is discussed. We presume gravity wave of very small amplitude as a source of dynamo E field modification. Internal gravity wave of extremely small amplitude cause d by ground motion interact with planetary scales waves below 10 km , and is amplified. The amplified IGW propagate to the dynamo region. Several observational facts which are favour to the generation of IGW are described. Finally we stress the need of satellite constellation in order to obtain the global morphology of ionosphere disturbance and to identify the mechanism, which at least provides us the material to judge applicability to future earthquake prediction.

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Characteristics of Ionospheric Electron Distribution for large Earthquakes around Japan

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Pre-seismic electron density anomalies have been widely discussed phenomena in ionospheric studies. However, it is not well-known what causes these anomalies. The other question is how to distinguish ionospheric anomalies from other disturbances such as geomagnetic storms. Therefore, a characterization and classification of magnetic storm and earthquake signatures is necessary for reliable forecasting. For this purpose, we investigate the similar and differing effects of magnetic storms and earthquakes on the ionospheric structure. In this paper, we mainly focused the time period after magnetic storms and before earthquakes. We select earthquakes occurred between 1998 and 2013 with M>6 and depth<30 km. We examined the temporal and spatial distribution of TEC using GIM-TEC data to detect the anomalous behavior and we found 28 earthquakes had anomalous changes. We further investigate their 3D distributions for these earthquakes with tomography and found 13 among them show the similar anomalous structure. Meanwhile, we select magnetic storms between 1998 and 2013 with Dst < -100 nT and the onset time from 6 am to 6 pm. Then, 42 magnetic storms were extracted. We analyzed arbitrarily 10 different storms and the same analyses were performed. We further employed the ionospheric foEs, NmF2 and hmF2 quantities as complementary data. Then, we prepared time series figures of these parameters and compared their responses against storm and earthquake effects. Results will be shown in the presentation.

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Estimates of Seismic Danger in Japan by Coherence Properties of GPS Noise

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The dense GPS network at Japan islands (more than 1300 stations) provides the data for detail investigation of the Earth surface tremor. We used 3-components GPS data with sampling time step 5 minutes which were downloaded from the site of Nevada Geodetic Laboratory since 2015.03.03 up to the current time. Maps of kernel estimates of probability density functions are presented for nodes of the regular net sized 30x30, which are realized the spatial maximum of the frequency-dependent maximal values of the multiple spectral function of coherence of GPS time series from the nearest 10 workable stations for all 3 components of GPS time-series within moving time window of the length 5 days. The GPS station is considered workable in the time window if its registration interval includes the considered time window and the number of missing values does not exceed a predetermined maximum allowable proportion of the total length equal to 0.1. The missed values are filled using information about records from neighbor time interval of the same length as the length of gaps. Before calculating the coherence function in each window the trend is removed by polynomial of 4th order and 3-sigma winsorizing was performed. The map of most frequent positions of frequency-dependent maximum of multiple coherence of GPS noise extracts Nankai Trough with maximum at the vicinity of the point 34N and 138E. This result is an independent confirmation of the earlier conclusion made by the analysis of seismic noise (http://dx.doi.org/10.4236/ns.2013.58A1001).

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Correlation between earthquake occurrence and the anomalous propagation of VHF radio waves indicated by the gain and the p-value of prediction maps produced by a simple objective algorithm in the Shimabara area, Kyushu, Japan

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Electromagnetic precursors associated with the impending earthquake, such as variations of geoelectric current, total electron contents in the ionosphere, and anomalous transmission of radio waves in the VLF or VHF band, have been observed (e.g. Hayakawa, 1996). Recently, some researchers have discussed how these precursory phenomena relate statistically to the impending earthquake (Le et al., 2010, Orihara et al., 2012, Hattori et al., 2013, Han et al. 2014). Anomalous (i.e., beyond the line of sight) VHF-band radio-wave propagation is one such claimed short-term precursor; physical preparatory processes of earthquakes may produce/attract electromagnetic scatterers in the area over the source of the impending earthquake (Kushida and Kushida, 2002, Moriya et al.,2010). Hokkaido University has been monitoring this anomalous propagation in several regions in Japan. On April 14th 2016, an Mw 6.5 earthquake occurred in Kumamoto, which was followed by a nearby greater Mw 7.3 event on April 16th. Just before these events, anomalous propagation of the VHF radio wave from an FM station in Miyazaki was observed at Shimabara receiving station. Epicenters of these Kumamoto events were between the broadcast and receiving stations. To evaluate the statistical significance of the tendency that such anomalies precede impending earthquakes in this region, we made a spatio-temporal map of earthquake alarm (though for only one spatial grid, which is the region between the Miyazaki broadcast and the Shimabara receiving stations) based on the data for 2015 to 2016; after anomaly appears, we turn ON the alarm for a certain period of time L, and thus divide the whole observation period into “Alarm ON", “Alarm OFF", and “Undecided (due to missing data)" periods. The alarm map was compared with the occurrence of local earthquakes with M > 4.5 after declustering. The result, the associated p-value was not low enough to suggest the statistical significance.

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Testing Geospace Technologies for Alerting Large Earthquakes: An Integrated Approach of Space and Ground Observations

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The most recent catastrophic earthquakes (Nepal 2015, Japan 2011, Haiti 2010, China 2009, Pakistan 2007, Sumatra 2004) were providing new information to the science community enabling new ideas in the development of earthquake hazard mitigation scheme. We are proposing a scheme requiring interdisciplinary use of latest geospace and remote sensing technology based on multi platform data observations. This multi sensory approach is analyzing atmospheric and ionospheric signals and searching for pre-earthquake signals by using geospace sensing techniques and ground data. The approach is still in an early stage of testing and is based on data fusion of satellite thermal observations (LEO, GEO) in conjunction with GPS/TEC (GNSS), atmospheric assimilation models and ground multi parameter continuous measurements. The proposed methodology uses existing satellite sensors and ground observations in One Web framework to study physical processes described by the Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) concept. Our initial test results show that simultaneous satellite and ground measurements, using as an integrated web, could provide earthquake short-term alert capabilities (several days) for major earthquake. The significance of initial results is discussed within the framework of the latest earthquakes in Nepal and Chile and major activities in 2013-16.

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Quantification of Seismic Hazards with Detrended Fluctuation Analysis of Time Series: Case Studies of the Japanese Islands and California

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We employ the approach of statistical physics to quantify current seismic hazards of two geologically active regions of the Earth: the Japanese islands and the west coast of the United States. Specifically, we apply a technique of fractal analysis of time series, a detrended fluctuation analysis (DFA) method [1], to study the evolution of displacements of the land surface and detect those areas of the Earth's crust that are evolving in a critical mode usually preceding a catastrophe. As the input data, we use freely available time series from GPS stations densely covering both regions of interest. The high density of the data allows producing detailed maps of the seismic hazard and highlighting the riskiest areas where disastrous seismic events are likely to occur in the future [2, 3]. Our findings also demonstrate that vertical and horizontal motions of blocks of the Earth's crust exhibit qualitatively different mechanisms of transition into critical states, which indicates the existence of a general nonlinear mechanism of appearance of critical (precatastrophic) regimes in open stochastic dynamical systems. The results of our analysis were partly confirmed by a recent earthquake struck in Fukushima, Japan, on 21 November 2016.

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Possible conjugated TEC anomalies preceding large earthquakes

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Ionospheric total electron content (TEC) enhancement instantly before the very large earthquake was first found after the 2011 Mw9.0 Tohoku earthquake [Heki, 2011]. Up to now, the similar enhancements were observed before eighteen earthquakes with moment magnitude from 7.3 to 9.2 [Heki and Enomoto, 2015; He and Heki, submitted]. Recently, He and Heki [2016] analyzed the spatial distribution of preseismic ionospheric anomalies of three large earthquakes in Chile, i.e. the 2010 Maule (Mw8.8), the 2014 Iquique (Mw8.2), and the 2015 Illapel (Mw8.3) earthquakes, and obtained the three-dimensional structures of the TEC anomalies for the 2015 event based on a projection approach. The observation result showed that the epicenter, the positive and negative anomalies distribute along the field-aligned direction, which resembles the simulation scenario [Kuo et al., 2014]. Besides this near epicenter phenomenon, another expected effect is the possible mirror ionospheric TEC anomalies associated with the geomagnetic field, i.e. the TEC anomalies are probably observed at geomagnetic conjugate points meanwhile. Here, we performed a systematic search for the possible mirror image anomalies that are to emerge at geomagnetic conjugate points based on GNSS TEC observations.

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Variations of statistical parameters of the background seismic noise before strong earthquakes in Kamchatka

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The network of broadband seismic stations of Geophysical service RAS works on the territory of Kamchatka peninsula in the Far East of Russia. We used a method for seismic noise analysis which is described in [1-2]. We used continuous records on Z-channels at 21 stations for creation of background seismic noise time series in 2011-2016 with sampling 1 minute. Average daily parameters of multi-fractal spectra of singularity have been calculated at each station using 1-minute records. Maps and graphs of their spatial distribution and temporal changes were constructed at time scales from days to six months. Also, the time series of daily median values of the statistical parameters of the noise were calculated on all stations.

Three strong earthquakes with magnitudes M=6.9–8.3 occurred near the Kamchatka peninsula during the observations. The synchronous variations of the background noise parameters and increase in the coherent behavior of the median values of statistical parameters was shown before two strong earthquakes 2013 (February 28, MW=6.9; May 24, MW=8.3) within 3–9 months and before the earthquake of January 30, 2016, MW=7.2 within 3–6 months.

Peculiarities in changes of statistical parameters at stages of preparation of strong earthquakes indicate an attenuation in high-amplitude outliers and the loss of multi-fractality in time series of noise. The changes in the various statistical parameters before strong earthquakes on Kamchatka corresponds to their behavior during the preparation of the strongest earthquakes near Japan in 2003, M=8 and in 2011, M=9.

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Clarification of the mechanism of VLF radiation intensity reduction before earthquakes observed by DEMETER and WWLLN data

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Statistical observations by DEMETER have shown that a decrease of the VLF EM wave intensity around 1.7 kHz the cut-off frequency of the Earth's-Ionosphere guide occurs a few hours before an EQ. It is thought that this effect arises from a disturbance in the D-region of the ionosphere.

To further investigate this phenomenon we have analyzed whistler signals observed on DEMETER data using also lightning data from the WWLLN network. Whistlers that travel through the ionosphere up to the satellite should indeed be good tracers of possible low altitude ionospheric disturbances that may, in particular, modify the absorption rate of the propagating EM waves.

Whistler measurements obtained on board DEMETER in March 2010 before the Sumatra EQ have been compared with similar observations performed before and after the EQ but during seismically quiet periods. Initial results are consistent with an increase in the whistler wave absorption up to a few dB a few hours prior to EQ that could result from an enhancement of about 10-15% of the electron density in the lower ionosphere.

In this presentation we report the data processing methodology based on the combined use of in-orbit (DEMETER) and ground-based (WWLLN) measurements and initial quantitative outcomes of the deduced ionosphere variations. Further studies are required to build the necessary statistical knowledge of the phenomenon and identify the spatial scales of the ionosphere disturbances.

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rdisciplinary approach towards earthquake prediction studies

Combining probabilistic seismicity models with precursory information: application to long-delayed aftershocks

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Quantitative assessments of increasing probabilities of earthquakes at a presence of precursors or precursory patterns still remain a big challenge. A strong and rising interest, however, is manifested last years to the methods of combining probabilistic seismicity models with any kind of precursory phenomena. Shebalin et al. (2014) have proposed a method to combine earthquake forecast rate-based models with any information that could locally increase the forecasted earthquake rates. The method is based on estimation of differential probability gains calculated in error diagram that evaluates the performance of the input information with respect to the reference model. The differential probability gain, that depend on a measurable quantity of the precursory phenomena, is then used at each point in space and time as an amplifying factor of the initial seismicity model. An important advantage of this combining method is its capacity to produce high expected rates. Recursive application of the method solves also a problem of the interdependence of the precursory phenomena.
In this talk I present first results on combining simple aftershock rate model with a precursory pattern of large aftershocks. The idea came from the premonitory analysis of the early aftershock statistics (forecasting algorithm EAST). In the considered case the EAST method is extended (but actuary drastically simplified) to the analysis of seismicity within aftershock sequences, and actually secondary aftershocks and main shocks, which are themselves aftershocks of the major main shock, are considered. The research was supported by Russian Science Foundation (Project N 16-17-00093).

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Nowcasting Global Earthquakes

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The term "nowcasting" refers to the estimation of the current uncertain state of a dynamical system, whereas "forecasting" is a calculation of probabilities of future state(s). Nowcasting is a term that originated in economics and finance, referring to the process of determining the uncertain state of the economy or markets at the current time by indirect means.

We have applied this idea to seismically active regions, where the goal is to determine the current state of a system of faults, and its current level of progress through the earthquake cycle (http://onlinelibrary.wiley.com/doi/10.1002/2016EA000185/full).

We wish to estimate how far the fault system has progressed through the "cycle" of large recurring earthquakes. We use the global catalog of earthquakes, using "small" earthquakes to determine the level of hazard from "large" earthquakes in the region. As an application, we can define a small region around major global cities, for example a "small" circle of radius 150 km and a depth of 100 km, as well as a "large" earthquake magnitude, for example M6.0. Also, the region of influence of such earthquakes is roughly 150 km radius x 100 km depth, which is the reason these values were selected.

The statistics are computed from a "large" region surrounding the "small" 150 x 100 km circle. The current count of earthquakes that is used to compute the nowcast is obtained from small earthquakes in the small region. The basic assumption is that both the "large" and "small" regions are characterized by the same Gutenberg-Richter magnitude frequency statistics.

We have used these techniques to compute the relative nowcast rankings of large global cities at risk for damaging earthquakes. In this talk we discuss these rankings. We also discuss the results of sensitivity analyses of the rankings to variations in the selected magnitude, small and large regions.

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integrated Study and Test for Earthquake Precursors (iSTEP-4)

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The iSTEP (integrated Study and Test for Earthquake Precursors) project goal is to study characteristics of seismo-ionospheric precursors in the total electron content and develop lithosphere-atmosphere-ionosphere (LAI) coupling models finding possible causal mechanisms for the large earthquake prediction and forecast of the globe. The project consists of a main project and three sub-projects (Sub-project I: Seismo-ionospheric/atmospheric precursors, Sub-project II: Seismo-lithospheric precursors, Sub-project III: Statistics for earthquake hazard). The Main project operates the integrated ground-based seismo-electromagnetic observation system in Taiwan and develop physical models to find possible mechanisms. The integrated observation system including seven networks of magnetometers, infrasonic wave systems, atmospheric electric field mills, Doppler sounding systems, ionosondes, GPS receivers, and all sky cameras. The observation system is used to monitor earthquake precursors in the lithosphere, the atmosphere, and the ionosphere, and to find the LAI coupling in Taiwan. Currently, it is the most comprehensive ground based system, which acts a reference for the earthquake precursor studies of the world. Meanwhile, Main project will utilize existing ionospheric physics models, such as TIEGCM, SAMI3, etc. to reproduce seismo-ionospheric precursors (SIPs) and seismo-atmospheric precursors (SAPs) observed by Sub-project I and seismo-lithospheric precursors (SLPs) by Sub-project II finding possible causal mechanisms and searching the LAI link. The observed and simulated precursors in the lithosphere, atmosphere, and ionosphere of a certain event will be further compared with its associated statistical results of Sub-project III to assess the hazard.

*S12-2-01
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Coupled interaction of deep Earth gases with quasi-static rupture of earthquake nuclei; possible source mechanism for seismo-EMs

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Various types of precursor anomalies preceding earthquakes have been reported in seismic, geodetic, geochemical and electromagnetic observations. Among them, recent advances in the seismo-EMs; especially GPS-TEC enhancements associated with strong earthquakes, represent a possible method by which to predict an imminent earthquake (Heki, GRL 2011). The underlying causal relationship still remain equivocal, although various proposals have been discussed on the topics.
In turn release of isotropic C13 and He3 influx from the deep crust reservoirs have been often detected; e.g. in the 2011 Tohoku-Oki earthquake (Sano et al. Nat. Comm. 2013). This fact suggests that the highly pressurized deep Earth fluids, as well as tectonic stress, play an important role in triggering of quasi-static rupture of earthquake nuclei. A new source mechanism for the seismo-EMs is needed to elucidate the underlying causal relationship between the hydro-mechanical and the electromagnetic processes.
Taking into account the coupled interaction of rock ruptures with the gas flowing-in as a working hypothesis (Enomoto, GJI 2012), we conducted laboratory experiments of uniaxial rock rupture with high-pressure CO_2 flow, where a flat-ended chisel equipped with a flow-channel was loaded against a rock block of 15-30 mm thick; quartz diorite and gabbro. The electric currents as high as 0.2-0.7 microampere, depending on the rock thickness, were successfully measured, followed for approximately a few milliseconds after fully development of the crack. The current flows are transient process, and the following gases are un-electrified, but they drive the preceding electrified gases; i.e. generation of the pressure-impressed current dipole. The model provides well-reasoned explanation for geomagnetic anomalies as observed in the 1965-1967 Matsushiro earthquake swarm and in the 2011 Tohoku-Oki earthquake.
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*S12-2-02
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rdisciplinary approach towards earthquake prediction studies

Multi-parameter assessments of pre-earthquake atmospheric signals

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We apply interdisciplinary observations to study earthquake processes, their physics and the phenomena that precede their energy release. Our approach is based on multi-sensors observations of short-term pre-earthquake phenomena preceding large earthquakes (M>6). The integrated satellite and terrestrial framework (ISTF) is our method for validation and is based on sensor web of several physical and environmental parameters (Satellite thermal infrared radiation (STIR), electron concentration in the ionosphere (GPS/TEC), air temperature/humidity measurements) that were found to be associated with earthquakes. The science rationale for multidisciplinary analysis is based on concept Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) (Pulinets and Ouzounov, 2011), which explains the synergy of different physical processes and anomalous variations, usually named short-term pre-earthquake anomalies. To check the predictive potential of pre-earthquake signals we validate different anomalous signals in retrospective and prospective modes including M6.0 Napa 2014, M6.0 Taiwan 2016 and M7.0 Kumamoto, Japan 2016. Our findings suggest that pre-earthquake signals (with 1-30 days time-lag) follow a general temporal-spatial evolution pattern, which has been seen in other large earthquakes worldwide. This study was coordinated under the project “Validation of Lithosphere-Atmosphere-Ionosphere-Magnetosphere Coupling (LAIMC) as a concept for geospheres interaction by utilizing space-borne multi-instrument observations“ supported by International Space Science Institute (Bern and Beijing).

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rdisciplinary approach towards earthquake prediction studies

Probability tomography and wavelet analysis of self-potential data and possible application in landslide monitoring

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Self-potential method is a kind of near-surface geophysical technique, which has been adopted in exploration of metal ore, monitoring of contaminants and natural hazards. This study focuses on the self-potential data processing. The source element occurrence probability tomography can give the probability of the source location and the charge property. Due to the limited resolution, the probability tomography method might yield ambiguous or even misguiding results in case of the multiple sources with a short distance. In order to overcome the above disadvantage and enhance the tomography effect, we combine the charge occurrence probability tomography with the complex wavelet transform method in self-potential data processing. We adopt the commercial finite element method (FEM) software COMSOL Multiphysics in the forward modeling. We apply the complex wavelet analysis the synthetic self-potential data obtained from the forward modeling of some given models. The results show that the complex wavelet analysis not only can locate the electric sources, but also can identify the electric features (e.g., homogeneity, inclined angle of dipole or polarized body, etc.). Furthermore, we apply the combined probability tomography and the continuous complex wavelet analysis to the synthetic self-potential data. The model test shows that the combined method could reduce the computation of 3D current source probability and enhance the imaging resolution. We also apply the combined method to the data from sandbox experiments and test the possible time-lapse tomography. This study may provide an effective approach of monitoring ground water flow, with potential application in landslide monitoring.

*S12-P-01
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Characterizing the nature of spatial heterogeneities based on multi-fractal and seismic b-value analysis of the 2015 Nepal earthquake sequence

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The multi-scaling nature of the spatial heterogeneities of the medium in the source region of the 2015 Nepal earthquake is investigated based on the multi-fractal and seismic b-value analyses of the aftershock sequence of the 2015 earthquake. The aftershock sequence exhibits an apparent multi-fractal structure, characterized by a spectrum of generalized dimension Dq varying from D2 = 1.61 to D22 = 0.1. We estimated the bias in Dq that may arise due to finite numbers of data points and limited size of study volume by comparing the true estimates with those obtained with uniform random distribution of point sets using the same numbers of events as for the real data. In addition, samples from the real data are randomly extracted and dimension spectra for these are examined as well. We also discussed the possibility of the apparent multi-fractality that may arise in case of finite data sets. Our results show that the spectrum for the uniform random generation is weakly multi-fractal by comparing the results from real data and simulated points sets that may help distinguish between true and apparent multifractality,that is expected for a data set with finite number of samples. Next, temporal correlation between the correlation dimension D2 and energy released shows a significant drop in D2 before the major events in the sequence, which tries to come back to the background value. The multi-fractal structure of Dq and their temporal variation suggest that the spatial distribution of aftershocks is not a random phenomenon, but it self-organizes on a spatio-temporal scale into a critical state, exhibiting a scale-independent structure governed by a power-law scaling. We also studied the frequency-size distribution of the sequence, characterized by the Gutenberg-Richter law with an average seismic b-value of 1.11±0.08. Our results are useful for seismic hazard assessment in the near field due to the subduction zone earthquake in the region.

*S12-P-02
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rdisciplinary approach towards earthquake prediction studies

Precursory signature of a megathrust earthquake and postseismic effects on regional earthquake induction

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The prediction of great earthquakes has not been successful despite various efforts. Finding a signature for impending great earthquakes is crucial for seismic hazard mitigation. We observed a temporal change of the Gutenberg-Richter frequency-magnitude relationship (b value) before the 2011 Tohoku-Oki megathrust earthquake for more than 20 years. It is observed that the b values decrease with time before the events. The change of b value of region is proportional to the cumulated stress. The megathrust earthquake caused large permanent lithospheric displacements in regional distances. The seismicity around the Korean Peninsula was increased significantly after the 2011 M9.0 Tohoku-Oki earthquake, which is not consistent with the expected seismic-quiescence. Strong seismic waves cause large dynamic stress changes, incurring fluid migration and increasing pore fluid pressure in the media. The lithospheric displacements directing to the epicenter on the convergent plate boundary develop transient radial tension field over the backarc lithospheres. The seismic velocities in the lithosphere changed abruptly up to 2 % after the megathrust earthquake, which recovered gradually with time for several years. The ambient stress field is recovered gradually as the induced stress field diminishes with time by tectonic loading. A series of moderate-size earthquakes and earthquake swarms occur as a consequence of medium response to the temporal evolution of stress field. The long-term evolution of seismicity is expected to continue until the ambient stress field is fully recovered.

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Resistivity changes during the 2015 seismic swarm detected by real-time magnetotelluric monitoring system in Taal volcano (Philippines)

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Taal volcano is located in the island of Luzon and 60 km south of the capital city of Manila. It is one of the most active volcanoes in the Philippines. The first recorded eruption was in 1573 and since then it has erupted a total of 33 times, with the last eruption in 1977. These eruptions resulted in thousands of casualties and considerable damage to property. In 1995 it was declared one of the "1990s decade volcano" by IAVCEI. Although the volcano remained fairly quiescent after the 1977 eruption, at the beginning of the 1990s it began to exhibit several phases of abnormal activities, such as episodes of seismic swarms, ground deformation and fissuring, and hydrothermal activities, all of which continues to the present. Past eruptions of Taal Volcano can be divided into 2 distinct cycles, depending on the location of the eruption: eruptions centered at the Main Crater (1572-1645 and 1749-1911); and eruptions occurring at the flanks (1707-1731; 1965-1977).
As part of the PHIVOLCS-JICA-SATREPS Project (2010-2014), magnetometers were installed at Taal volcano. These consist of three (3) Overhauser-type magnetometers (installed at VTBM, VTDK and VTMC) and one (1) fluxgate-type magnetometer (installed at VTBM). The Project also established (using magentotelluric method) that a large hydrothermal reservoir is underneath Taal volcano and currently this is under a state of equilibrium. The state of the hydrothermal reservoir is thus monitored constantly by magnetometers. In early-2015, remarkable resistivity changes were detected by the flux-gate magnetometer during an earthquake swarm occurred in Taal volcano. The locations of these earthquakes appears to be in the approximate location of the hydrothermal reservoir.

*S12-P-04
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Characteristics of b-value and TEC changes in Space and Time before the Large Earthquakes in Japan

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In recent years, there are many reports on electromagnetic phenomenon preceding large earthquakes. Anomaly of the total electron content (TEC) is one of the most promising anomalies for the short-term earthquake forecast. However, the TEC is disturbed by solar-terrestrial interaction very much. Therefore, it is difficult to discriminate anomalous changes on earthquakes and solar activities easily at the moment. On the other hand, it is reported that the b-value around the epicenter region decreases prior to the large earthquake. In this paper, we investigate the effectiveness of the integrated analyses on the b-value and TEC analysis. We select the 2003, 2008 Tokachi-oki EQs and the 2011 Tohoku-oki EQ at first. As results, we found the variation of b-value has a tendency to decrease for M7class EQs in the analyzed regions and the neighbor's area. For the 2003 Tokachi-oki EQ, we found decrease of b-value 16 days and 2-3days before the main shock. On the other hand, for the TEC anomaly in the Hokkaido region, we found significant increase 2 days before the EQ(M>6.0,D<40 km) using the statistical analysis during 1998-2015. That is, the positive anomaly is dominant, In the case of the 2003 Tokachi-oki EQ, TEC anomaly occurred 2 days before main shock. These results suggest the effectiveness of the proposed method. We have the similar tendency for the 2011Tohoku-oki EQ. Details will be given in the presentation.

*S12-P-05
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Anomalies of astronomical time-latitude observations before strong earthquake and discussions on the problems of its application

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Strong earthquake may create a large number of casualties and huge property losses. Due to the complexity of crustal structure and movement, the geophysical process during the gestation and occurrence of earthquake is extremely complex. So it is very difficult to forecast an earthquake in advance. To find effectual earthquake precursors is one of the key for meliorating earthquake prediction. A phenomenon that short-term anomalies appeared in residuals of astronomical time and latitude observations before major earthquakes, which occurred in regions around the astrometric instruments, was discovered by Chinese astronomers after Tangshan Earthquake in 1976. The phenomenon was called anomalies of residuals of astronomical time and latitude observations (ATLR). The major characteristics of the phenomenon have been studied preliminarily. ATLR anomalies may be from the variation of the vertical, which is the datum line of such astrometric instruments, due to the motion of underground mass.
The possibility that using the observations to provide information for strong earthquakes in advance has been researched and related tests to provide forecast information have made in China. Present results and tests showed that the phenomenon would possibly become a kind of significant short-term earthquake precursors. However, observations of one instrument can only reflect the vertical variations within a certain range around the instrument, so ATLR of one station cannot afford the information of position and magnitude of an earthquake. To set up an network using seemly astrometric telescopes in seismogenetic zone will be needful for finding significant forecasting information. The new Digital Zenith Telescope (DZT) which has characters of high precision, robotization, miniaturization and low cost was made in China recently years. DZT is propitious to set up such network. The scheme on setting up network is put forward. The notions and problems related to network are discussed.

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rdisciplinary approach towards earthquake prediction studies

Abnormal seismicity of slow earthquakes on land prior to 2011 Tohoku earthquake

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Slow earthquake (EQ) has recently gained much attention as a possible precursor of large earthquake. A number of studies so far suggest that slow EQ (or slow slip) may serve as an indicator of stress accumulation/transfer, thus quite useful for predicting a large earthquake. Indeed, it was observed that slow EQs migrated toward the epicenter of 2011 Tohoku earthquake, which suggests a possible nucleation process prior to the occurrence of the megathrust earthquake. As regards Tohoku EQ, the current focus of research tends to be on off-shore areas near the epicenter, exploring relationships among slow tremors, slow slip events and the megathrust earthquake. On the other hand, slow EQs that occurred in remote areas (on land) far from the epicenter receive less attention. Nonetheless, geodetic data suggest that the accumulation of on-land stress in Tohoku region is associated to that of the off-shore one. So, we cannot rule out a possibility of abnormal seismicity in on-land slow EQs prior to Tohoku EQ. In this talk, we discuss such a possibility, examining the relationship between slow EQs in remote areas and Tohoku EQ in a data-driven approach. First, we analyze on-land slow EQ that occurred in northern Japan in the last 20 years (based on the catalogue of Japan Meteorological Agency) by means of cluster analysis. In this analysis, three subtypes of slow EQs are identified, which are statistically characterized by short, mid and long-term intertime between slow EQs. Second, it is found that the short and mid-term slow EQs became quiescent two months and one month before the Tohoku EQ, respectively. Such a phenomenon is not observed in generic earthquakes, and would be identified with a unique characteristic of megathrust earthquakes. Finally, we apply OFC (Olami, Feder, Christensen) model to the slow EQ data in question, giving a theoretical interpretation to the aforementioned phenomenon.

Challenges in moment tensor resolution: collapses, explosions and shallow earthquakes

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Regional moment tensor inversion is extensively used to model the earthquake rupture geometry and estimate earthquake source parameters. Typically, inversion algorithms derive the moment tensor configuration by fitting low frequency full waveforms or amplitude spectra. Resulting moment tensor catalogues provide a valuable information on seismic source processes. They can be used for seismotectonic interpretation, to discuss non shear ruptures or as a base to investigate the stress orientation. The resolution of the moment tensor can be reduced by several causes, such as waveform mismodeling due to a poor knowledge of the crustal structure, low signal-to-noise ration due to seismic noise and poor azimuthal coverage due to an unfavourable network geometry. Poor conditions may bias moment tensor solutions, for example introducing non double couple terms. Beside these known problems, the procedures of moment tensor inversion, decomposition and interpretation are also affected by intrinsic ambiguities, which can become critical for shallow sources or specific source-network geometries. First, different uncertainties affect different moment tensor entries, resulting in an uneven resolution of moment tensor components. In addition, moment tensor components trade-offs affect the uniqueness of the solution, so that different moment tensor configurations may fit well the data. Finally, the interpretation of the moment tensor solution may be hindered by the chosen decomposition. We discuss and investigate some of these often neglected problems and provide example for each of them, combining synthetic tests with the discussion of significant real data applications. Among the real data cases, the analysis of seismic signals produced by recent volcanic collapse and shallow underground explosions in North Korea helps to illustrate the problem of moment tensor uncertainties, trade-off and decomposition.

*S13-1-02
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Uncertainties in moment tensor estimation for induced earthquakes illustrated at the example of the Groningen gas field, The Netherlands

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The Groningen gas field is one of the largest gas fields in the world, in production since 1963. Since the early 1990's, induced seismicity started to occur in its vicinity. Approximately 220 earthquakes with M ⊠ 1.5 were registered from 1991 to July 2013 in the vicinity of the Groningen field area. The strongest event recorded so far (ML = 3.6) occurred on 16th August 2012 near the village of Huizinge, raising huge damage claims as well as public concerns.

Starting in 1991, a geophone monitoring network operated by KNMI was installed. This network has been extended several times, providing a detection threshold of M=1.5 since 1995. We will use a newly developed python-based probabilistic moment tensor inversion tool named “Grond" to re-analyse four events that occurred from 2006 to 2009, for which focal mechanisms have been computed earlier (Kraaijpoel and Dost, 2012).

Each of the four events has been recorded on up to 6 accelerometers at distances of less than 10 km and on up to 8 shallow borehole strings at distances of 15 to 90 km. Due to the inherent capabilities of probabilistic methods, we are able to analyse trade-offs between inversion parameters and to assess uncertainties. We illustrate the influence of parameters of the forward modelling and the choice of the objective function on the resulting moment tensor.

“Grond" adapts an optimization scheme using elements of simulated annealing and the bootstrap technique. Rather than optimizing a single objective function, it tries to find volumes in parameter space that satisfy low misfit values over an ensemble of N variations of the objective function. In every optimization method, there is a trade-off between number of tested models and ability to find the global minimum without getting trapped in local minima. Usually a compromise is made depending on the characteristics of the problem to be solved. In our optimization, however, the degree to which the parameter space is explored can be tuned by the user.

*S13-1-03
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Moment tensor inversion based on the principal component analysis: Method and application to the 2014 earthquake sequence in West Bohemia, Czech Republic

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We develop and test a new hybrid approach of the amplitude and waveform moment tensor inversions, which utilizes the principal component analysis of seismograms. The proposed inversion is less sensitive to noise in data being thus more accurate and more robust than the amplitude inversion. It also suppresses other unmodelled phenomena like a directivity of the source, errors caused by local site effects at individual stations and by time shifts in arrivals of observed and synthetic signals due to an inaccurate velocity model. The inversion is simple and computationally less demanding than the full waveform inversion and thus applicable to large datasets. The approach is numerically tested on synthetic data with a various level of noise. The applicability of the inversion is demonstrated on inverting more than 800 microearthquakes that occurred during the 2014 activity in West Bohemia, Czech Republic. The analysis revealed clustering of the moment tensors into several distinct types. Three types of MT are left-lateral strike slips associated with the most active fault in the focal zone. Another cluster is characterized by the right-lateral strike slips associated with the fault conjugate to the main fault. Finally, we identified a cluster with pure reverse focal mechanisms which are anomalous and not expected to occur in the region. These mechanisms were not detected in the previous seismic activity and they have an unfavourable orientation with respect to regional tectonic stress. This might indicate a presence of local stress heterogeneities caused, for example, by an interaction of faults or fault segments in the focal zone.

Non double couple components of Mw>4.5 events in The Geysers geothermal field, California revealed by a hierarchical Beyesian inversion

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Earthquakes occurring in geothermal and volcanic environments can have significant non double couple (non-DC) components related to fluid movement. However, significant non-DC components can also emerge as a consequence of not adequately (or not at all) accounting for the noise in the data in routine waveform inversions for earthquake source parameters. Here, we apply a hierarchical Bayesian moment tensor inversion method to a number of earthquakes from The Geysers field in California using data from broadband stations at regional distances. This probabilistic technique yields parameter uncertainties that indicate the reliability of the non-DC components. Furthermore, we allow the noise to determine the level of data fit by treating it as a parameter in the inversion, and account for interdependence of data errors using an empirically estimated noise covariance matrix.

The structure of The Geysers field involves stacks of permeable and impermeable highly fractured rocks, probably underlain by a magma body. Seismicity is dominated by microearthquakes, half of which have significant non-DC components. We have analysed several Mw>4.5 events using two different assumptions about the noise (two different noise covariance matrices).

The double couple components of the sources are consistent with strike-slip or normal faults present in the geothermal field, and the non-DC components show a variety of values. Inversions with the empirically estimated cosine covariance matrix result in a slightly lower isotropic component than inversions with a pure diagonal covariance matrix. One event is predominantly a double couple, while the others have significant non-DC components. They can be explained as a combination of shear faulting and crack opening, but at least one event requires an additional mechanism that reduces the isotropic component, such as fluid extraction.

Determination of high precision microseismic source mechanism by iterative relative moment tensor inversion

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Source mechanism of microearthquakes provides fundamental information about the physical process at the source, in-situ stress field, etc. However, their reliable estimate is still a difficult task due to our poor knowledge of the underground structure. Dahm (1996) developed a novel method of source mechanism determination for earthquake clusters called relative moment tensor inversion (RMTI), in which relative body-wave amplitudes for two earthquakes recorded at a common station are used to eliminate the effect of un-modeled propagation paths. If the source mechanism of one of those earthquakes is known a priori, the other source mechanisms can be determined without a computation of Green's function. A difficulty in this method is that errors in the mechanism of reference events may lead to biased solutions for other events.

To resolve this problem, we propose a method that iteratively applies the RMTI to source clusters improving each moment tensor as well as their relative accuracy. The procedure is as follows:
(1) Sample co-located multiple earthquakes with focal mechanisms, as initial solutions, determined by an ordinary method.
(2) Apply the RMTI to estimate the source mechanism of each event relative to those of the other events.
(3) Repeat the step 2 for the modified source mechanisms until the reduction of total residual converges.

Numerical tests showed that the solutions were successively improved by iteration and almost reached the input mechanisms. Even in the case of poor observation condition, we could obtain reliable estimates by imposing a DC constraint. Application to natural earthquakes revealed a small-scale heterogeneity which could not be identified by earthquake locations. The proposed method also has a potential to resolve real non-DC components, so our next plan is to apply the method to induced microseismic events in oil, gas, and geothermal fields, in which the relation between fluid injection and non-DC components is an important issue.

Microseismic Event Relocation and Focal Mechanism Estimation Based on PageRank Linkage

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Microseismicity associated with enhanced geothermal systems (EGS) is key in understanding how subsurface stimulation can modify stress, fracture rock, and increase permeability. Large numbers of microseismic events are commonly associated with hydroshearing an EGS, making data mining methods useful in their analysis. We focus on PageRank, originally developed as Google's search engine, and subsequently adapted for use in seismology to detect low-frequency earthquakes by linking events directly and indirectly through cross-correlation (Aguiar and Beroza, 2014). We expand on this application by using PageRank to define signal-correlation topology for micro-earthquakes from the Newberry Volcano EGS in Central Oregon, which has been stimulated two times using high-pressure fluid injection. We create PageRank signal families from both data sets and compare these to the spatial and temporal proximity of associated earthquakes. PageRank families are relocated using differential travel times measured by waveform cross-correlation (CC) and the Bayesloc approach (Myers et al., 2007). Prior to relocation events are loosely clustered with events at a distance from the cluster. After relocation, event families are found to be tightly clustered. Indirect linkage of signals using PageRank is a reliable way to increase the number of events confidently determined to be similar, suggesting an efficient and effective grouping of earthquakes with similar physical characteristics (ie. location, focal mechanism, stress drop). We further explore the possibility of using PageRank families to identify events with similar relative phase polarities and estimate focal mechanisms following Shelly et al. (2016) method, where CC measurements are used to determine individual polarities within event clusters. Given a positive result, PageRank might be a useful tool in adaptive approaches to enhance production at well-instrumented geothermal sites. Prepared by LLNL under Contract DE-AC52-07NA27344.

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Demonstration of improved seismic source inversion method of tele-seismic body wave

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Seismic rupture inversion of tele-seismic body wave has been widely applied to studies of large earthquakes. In general, tele-seismic body wave contains information of overall rupture process of large earthquake, while the tele-seismic body wave is inappropriate for analyzing a detailed rupture process of M6˜7 class earthquake. Recently, the quality and quantity of tele-seismic data and the inversion method has been greatly improved. Improved data and method enable us to study a detailed rupture process of M6˜7 class earthquake even if we use only tele-seismic body wave. In this study, we demonstrate the ability of the improved data and method through analyses of the 2016 Rieti, Italy earthquake (Mw 6.2) and the 2016 Kumamoto, Japan earthquake (Mw 7.0) that have been well investigated by using the InSAR data set and the field observations.
We assumed the rupture occurring on a single fault plane model inferred from the moment tensor solutions and the aftershock distributions. We constructed spatiotemporal discretized slip-rate functions with patches arranged as closely as possible. We performed inversions using several fault models and found that the spatiotemporal location of large slip-rate area was stable.
In the 2016 Kumamoto, Japan earthquake, the slip-rate distribution shows that the rupture propagated to southwest during the first 5 s. At 5 s after the origin time, the main rupture started to propagate toward northeast. First episode and second episode correspond to rupture propagation along the Hinagu fault and the Futagawa fault, respectively. In the 2016 Rieti, Italy earthquake, the slip-rate distribution shows that the rupture propagated to up-dip direction during the first 2 s, and then rupture propagated toward northwest.
From both analyses, we propose that the spatiotemporal slip-rate distribution estimated by improved inversion method of tele-seismic body wave has enough information to study a detailed rupture process of M6˜7 class earthquake.

A Bayesian hierarchical model for a seismic source inversion

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A source inversion analysis using spatio-temporal displacement field data is able to be formulated as a discrete linear inverse problem when the Green function and the source fault are known. However, it is difficult to calculate an accurate Green function. Previous studies approximated the effects of the uncertainty of the Green function by introducing a new correlated or uncorrelated error term, which is added to data. The approximation fails to capture important characteristics such as peak shift and heavy tails of the likelihood function under the uncertainty of the Green function.

We propose a hierarchical Bayes model for a multi-data analysis with the multi-time-window finite fault parameterization. In the model, a Green function is treated as a realization of a random variable G. The marginalization of the hyperparameters, which control the prior distribution of the model parameters and the observation errors, is approximated by plugging in of the maximum a posteriori hyperparameters given G. The marginal likelihood function for G is approximated by the Laplace approximation. The marginalization of G is approximated by a Monte-Carlo integration method.

We applied the method to synthetic data. We set a 1-D velocity structure at the source region. We drew thousands of velocity structure samples from the prior distribution of the velocity structure, and then calculated the corresponding Green functions. For reference, we also conducted a conventional inversion, which used only a reference velocity structure. We found that the conventional inversion result suffers from artifacts especially at the later shallow part of the rupture process, while the result with the proposed method does not suffer from the artifact. Note that the mitigation of the artifact was not possible with the simple mean-of-the-posterior-mean approach. We also found increase of the variance of the posterior distribution of the potency due to the marginalization of G.

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Seismicity of the Nordland area, Norway

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The Nordland area (65-70N; 8-18E) is tectonically active part of Norway. Enhanced seismicity may reflect on off-shore subsidence combined with the uplift of landmasses usually attributed to glacial isostatic adjustment (related to Pleistocene unloading). Detailed monitoring of seismic activity in the Nordland area was done in August 2013 – June 2016 as a part of the NEONOR2 project and information obtained from analysis of earthquakes together with geodetic data should be the key inputs for modeling of deformation and uplift patterns and their mechanisms in the region. A local network of 26 broadband stations was deployed and together with the permanent NNSN stations in that area, it contained 33+ stations within span 350 x 200 km. About 1250 earthquakes of M>0.0 was recorded during the project period and new map of seismicity of that area was retrieved. The main aim of the project is to reveal the stress field in that particular region and therefore the determination of stable focal mechanisms is crucial. Despite the high number of stations, enough clear polarity readings (>=6) were obtained for only about 20 strongest events (M<3.2). Hence we developed a methodology using automatic amplitude readings and the standard tools (FOCMEC, HASH) for focal mechanism determination which are implemented in SEISAN. The methodology is tested using the strongest events and conclusions for further application are suggested.

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earthquake statistics, spatiotemporal distribution of foci and source mechanisms as a key to understanding of causes leading to the West Bohemia/Vogtland earthquake swarms

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The origin of earthquake swarms is still unclear. West Bohemia-Vogtland represents one of the most active intraplate earthquake-swarm areas in Europe. There were swarms in 1997, 2000, 2008 and 20011 followed by reactivation in 2013 which forming a focal belt of about 15 x 6 km, focal depths vary from 6 to 15 km. An exceptional non-swarm activity up to magnitudes ML = 4.5, stroke the region in 2014, the events were also located in the NK focal belt.
We analysed geometry of the NK focal zone applying the double-difference method to seismicity in the period 1997 – 2014. The swarms are located close to each other at depths between 6 and 13 km. The most events obey the b-value = 1.0 distribution, however, a group of the largest events (˜ML > 2.8) depart significantly from it. Furthermore, we disclose that all the ML > 2.8 swarm events, which occurred in the given time span, are located in a few dense clusters. It implies that the most of seismic energy in the individual swarms has been released in step by step rupturing of one or a few asperities. The mechanism patters of the individual swarms indicate their complexity. MTs of the most analysed events signify pure shears except for events the second phase of the 1997 swarm the MTs of which indicate significant amount of non-DC components.
We infer that the individual earthquake swarms in West Bohemia-Vogtland are mixture of the mainshock-aftershock sequences which correspond to step by step rupturing of one or a few asperities. The swarms occur on short fault segments with heterogeneous stress and strength, which may be affected by crustal fluids. Pressurized fluids may reduce normal component of the tectonic stress and lower friction. Thus, critically loaded and favourably oriented faults are brought to failure and the swarm activity is driven by the differential local stress.

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Induced seismicity of Kuzbass (Russia). Bachatskoe earthquake of 2013, ML=6.1

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The Kuznetsk coal basin (Kuzbass) is one of the largest coal deposits in the world, located in the South of Western Siberia in Russia. The territory of Kuzbass has always proved itself as a district with rare large earthquakes and a moderate seismicity, much of which is concentrated in mountainous framing of the Kuznetsk basin. But a special study of induced seismicity was not carried out until the beginning of the century because of the sparse network of seismic stations here. Only in recent years in connection with the development of a network of seismic monitoring stations in the Kuzbass and conducting several observations using temporary networks of seismic stations has been shown the existence of induced seismicity. At the moment, the basis of the system of monitoring induced seismicity with 11 additional stations on the territory of Kuzbass is created. The system works in real time and allows tracking the appearance and the development of dangerous human induced seismic processes formed around mines and quarries. According to registrations of the system shown the induced seismicity in the Kuzbass significantly dominates over the natural seismicity.
In addition, a strong earthquake with ML=6.1 occurred on the 18th of June, 2013 near one of the largest open pits of the Kuznetsk basin (Bachatskiy). As a result of studies using temporary seismic stations in the epicentral area of the Bachatskoe earthquake was found that the seismic process area is closely connected to an open mine workings, and earthquakes are extended in the depth from the cut bed up to 4-5 km. Seismic regime of induced activation is continuous and not stationary. The orientation of the nodal planes of Bachatskoe earthquake focal mechanism corresponds to the direction of technogenic impact. The findings suggest that Bachatskoe earthquake and associated activation are induced earthquakes with a fairly large energy.

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Crustal stress field in Taiwan inferred from regional-scale damped inversion of a newly derived homogeneous earthquake focal mechanism dataset

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A regional seismic stress field of the crust in Taiwan has been obtained by applying the damped stress inversion algorithm to a newly derived focal mechanism dataset. To construct this homogeneous dataset, which is composed of more than 3000 centroid moment tensor solutions, we have developed a new multiple solution method to invert the high quality broadband waveforms collected in the past two decades. Only solutions with high quality and shallower focal depth (<40 km) are selected in the stress inversion. To test the reliability of the stress field, we implement a series of checkerboard tests with various grid spacing. Our results show that the maximum principle seismic stress, signma-1, is dominated by the NW-SE collision direction between the Eurasia plate and the Philippine Sea plat. It presents a fan-shape distribution in the western part of Taiwan. A dramatic change of sigma-1 direction at ~24.3N along the eastern coast, which may mark the transition from collision to subduction in the NE Taiwan area. In addition, we also notice that there is an S-shape trajectory across the Central Range that is suspected to be associated with spatial rheology heterogeneity. Normal faultings are mainly observed in the Okinawa Trough, Central Range, and SW offshore Taiwan, which are referred to different tectonic processes in this region. Obvious interface focal mechanisms in the eastern offshore region are also delineated with their NS striking and shallow angle thrusting pattern. Our principle seismic stress axes are comparable with the principle strain axes derived from GPS observation, implying that the crust in Taiwan may deform largely in an elastic manner. However, remarkable rotational patterns of sigma-1 presented in Ilan and Pingtung area may reflect the complicated tectonic forces and geological settings in the Taiwan region.

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Tidal controls on earthquake size-frequency statistics

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The possibility that tidal stresses can trigger earthquakes is a long-standing issue in seismology. Except in some special cases, a causal relationship between seismicity and the phase of tidal stress has been rejected on the basis of studies using many small events. However, recently discovered deep tectonic tremors are highly sensitive to tidal stress levels, with the relationship being governed by a nonlinear law according to which the tremor rate increases exponentially with increasing stress; thus, slow deformation (and the probability of earthquakes) may be enhanced during periods of large tidal stress. Here, we show the influence of tidal stress on seismicity by calculating histories of tidal shear stress during the 2-week period before earthquakes. Very large earthquakes tend to occur near the time of maximum tidal stress, but this tendency is not obvious for small earthquakes. Rather, we found that tidal stress controls the earthquake size-frequency statistics; i.e., the fraction of large events increases (i.e. the b-value of the Gutenberg-Richter relation decreases) as the tidal shear stress increases. This correlation is apparent in data from the global catalog and in relatively homogeneous regional catalogues of earthquakes in Japan. The relationship is also reasonable, considering the well-known relationship between stress and the b-value. Our findings indicate that the probability of a tiny rock failure expanding to a gigantic rupture increases with increasing tidal stress levels. This finding has clear implications for probabilistic earthquake forecasting.

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A statistical characterization of earthquake initiation and its implication

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Rapid magnitude (M) determination is critical for earthquake early warning (EEW). A number of methods have been proposed to do this. For example, the use of the frequency content of initial P wave (e.g., Allen & Kanamori, 2003), or a combination of displacement amplitude and a ground motion prediction equation (e.g., Odaka et al., 2003) or from the time between the onset of a body wave and the peak amplitude arrival of that wave (e.g., Noda et al., 2016). It is an essential question for these techniques whether or not the final M is deterministic at the time of initiation (e.g., Olson & Allen, 2005). To investigate this issue, Noda & Ellsworth (2016, GRL) used Japanese K-NET data from 150 events with 4.5 <= Mw <= 9.0 and hypocentral distance (R) less than 200 km, and examined the P-wave absolute displacements. They found that the P-wave displacement began in a similar way at the onset and departed from the similarity earlier for smaller events. In the magnitude range up to Mw 7, the scaling relation between the departure time (Tdp) and the final Mw resulted in $Mw = 2.29 * \log Tdp + 5.95$ which suggests that Tdp occurs before the completion of rupture in a statistical sense. Noda & Ellsworth indicated that the scaling relation was consistent with what Olson & Allen (2005) called the deterministic property of earthquakes in which the P-wave frequency contents (tau-p) scales with the final M even when the time window is significantly shorter than the typical source duration. Here we discuss how such a deterministic property could be explained by the model of Murphy & Nielsen (2009) where the available elastic energy at the initial rupture patch must exceed a certain threshold in order for the rupture to propagate spontaneously far beyond the initial patch. When the energy lies below the threshold, the final M is statistically deterministic at the time of initiation. When the energy exceeds the threshold, final M cannot be reliably determined from initial P wave alone.

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Effective stress drop of earthquake clusters

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The static stress drop is a standard measure of the average decrease of shear stress on a fault during an earthquake. It has been observed that stress drop does not vary significantly with earthquake magnitude and may be regarded as an invariant parameter of the rupture process at different scales. While typical stress drops of earthquakes range between 1 and 10 MPa, much smaller stress drops in fractions of MPa are reported for slow earthquakes and in some cases also for earthquake swarms. For the latter cases, the effective stress drop was introduced as an alternative parameter, which makes use of the cumulative seismic moment and total activated area of the seismic cluster.
We test how the effective stress drop is comparable to the static stress drop of a single earthquake rupturing the same fault portion. To this purpose, we compare the spatiotemporal evolution of the seismic moment release and analyze the uncertainties of the resulting stress drop estimates. We show that the effective stress drop is only comparable to earthquake stress drops in very specific cases. In particular, the effective stress drop values significantly underestimate the earthquake stress drops in the presence of aseismic deformation. Furthermore, the values are only scale-independent if pre-stress and post-stress conditions are uniform in space. Our analysis of data from injection-induced seismicity, natural earthquake swarms and aftershock sequences shows that in most cases the effective stress drop estimate is rather stable during the cluster evolution. However, slightly increasing estimates for injection-induced seismicity are indicative for the local forcing of the system, while overall low effective stress drop values hint to the important role of aseismic deformations.

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Radiated Energy Enhancement and Rupture Complexity of Large Subduction-Zone Earthquakes

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The rupture characteristics of large earthquakes on subduction zone plate boundaries vary substantially. The asperity model, proposed in the early 1980s, related variations of the largest earthquake size and complexity in a region to stress heterogeneity. Repeating earthquakes and geodetic measurements of inter-seismic strain accumulation support the notion of asperities being surrounded by creeping regions with different frictional properties. The surge of large earthquakes over last decade and the advance in observations and analysis techniques allow us to evaluate whether asperities differ from region to region. To quantify variable rupture complexity, we introduce a new energy radiation parameter, the radiated energy enhancement factor (REEF): the ratio of directly measured broadband radiated energy to the calculated minimum radiated energy for an event of equal seismic moment and duration with parabolic shape moment-rate function). For large earthquakes, REEF is closely related with complexity in the observed moment-rate function. We find that (1) REEF variation among different subduction zones is consistent with the level of segmentation proposed in the asperity model; and (2) REEF values are similar for earthquakes with different magnitudes in each region. Both observations indicate that the regional “asperity" structure observed at scales of tens to hundreds of kilometers is similar to that at smaller scales. Asperities thus differ from region to region, likely due to variable stress conditions on the plate boundaries.

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Seismic energy release at the seismogenic zone of Guerrero, Mexico.

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To study the mechanisms that control seismic energy release along the Guerrero, Mexico, subduction zone, we estimated radiated seismic energy, stress drop and radiation efficiency of two recent large earthquakes and their aftershocks. The first earthquake occurred at the border of the states of Guerrero and Oaxaca in Ometepec on March 2012 (Mw7.5), the second earthquakes occurred 300 km away, in Papanoa on April 2014 (Mw7.2). Estimations of radiated energy scaled with seismic moment (Es/M0), show no evidence of dependence of radiated seismic energy with distance from the trench, depth, or size of earthquakes. However, scaled energy distribution behaves in a heterogeneous way parallel to the trench, and it might be influenced by lateral heterogeneities along the subduction interface. Stress drop and efficiency also reveals rough changes parallel to the trench, in a similar way as scaled energy. However, results show that Ometepec earthquakes had lower stress drops and higher radiation efficiency values compared with Papanoa sequence.

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Seismic source spectra and the relation between corner frequency and source properties derived from spontaneous rupture of a circular fault

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Stress drop is an important dynamic source parameter for understanding the physics of source processes. The estimation of stress drops for moderate and small earthquakes bases on the measurements of corner frequency, seismic moment and a specific theoretical model of rupture behavior. As so far, there are several theoretical rupture models. However, different models will cause big difference for the estimation of stress drop, even in an idealized scenario of circular earthquake rupture. Moreover, those models are just kinematic models or quasi-dynamic models. Compared to previous models, we use the BIEM to simulate spontaneous dynamic rupture in homogeneous elastic full space and then to investigate the relation of corner frequency, seismic moment and source dynamic parameters. For unstable rupture, the relation between corner frequency and dynamic parameters coincides with that in previous models. One asymptote of the relation between the stress drop and the ratio of seismic moment and rupture radius is close to Eshelby's analytical solution for uniform stress drop. For self-arresting rupture, the scaling laws of corner frequency, seismic moment and stress drop are contrary to those for unstable rupture. Meanwhile, because corner frequency and seismic moment are two independent parameters obtained directly from observation, we check the relation between corner frequency and seismic moment. No matter whether rupture front for self-arresting rupture arrives at the barrier boundary or not, the relation between corner frequency and seismic moment coincides with the relation obtained from observation in which the corner frequency is inversely proportional to seismic moment. However, for unstable rupture, the relation between corner frequency and seismic moment cannot fit the observation.

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Earthquake Source Spectral Studies beyond the Standard Omega-Square Model

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A scientific methodology is to understand natural phenomena as general properties and variation around them. As for earthquakes, source spectral studies have simplified the information from seismic data and helped us enhance our knowledge of earthquake rupture process. The standard model in spectral studies is the omega-square model, where the source spectrum is flat equivalent to the seismic moment at lower frequencies and inversely proportional to the square of frequency at higher frequencies. The corner frequency borders the lower and higher frequencies and is related to the inverse of the source duration, therefore employed for estimating representative stress drop under an assumption of circular crack model. The omega-square model and the corner frequency represent the general property and the variation, respectively.

Recent studies in earthquake source spectra have been examining the validity of the omega-square model as a general model. Denolle and Shearer (2016) claimed the existence of another corner frequency which is scaled by Mo^(-1/5), for M > 5.5 earthquakes. However Uchide and Imanishi (2016) claimed that small earthquakes also have two corner frequencies, whereas some of small earthquakes are fitted well by the single-corner-frequency model, as revealed by a spectral ratio analysis using many empirical Green's function events for each target event.

We show the universality of the double-corner-frequency source spectra by analyzing small inland earthquakes in Japan by the method of Uchide and Imanishi (2016). In addition, as a byproduct of the study, the same analysis indicated the underestimation of the size of microearthquakes by the local magnitude scale, which significantly affects the b-value estimation.

Then what is the physical meaning of the second (higher) corner frequency? It is still difficult to answer this question, and we need case studies and scaling studies on the second corner frequency.

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Eccentric by-players of the 2011 Mw 9.1 Tohoku earthquake

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We analyzed the low rate GPS displacement records of GEONET and the continuous stress record at TOS of TRIES (about 600 km away in an azimuth of N120W) due to the 2011 Tohoku earthquake. This led us to a recognition of the tree eccentric by-players as below.
(1) Super sub-event of Mw8.4
We perceived a dominant single SH pulse of a width of around 30 s propagating with 3.9 km/s to stations of epicentric distances of hundreds of kilometers in record sections of a transverse component of the records. The SH pulse can not be elucidated by subfault/asperity of low angle thrusting along the subduction interface. Matching synthetic waveforms in a half space to the SH pulse in trial and error approach, we obtained a extraordinary subfault model in which slip velocity and seismic moment were around 10 m/s and (4-5)**21 Nm (Mw 8.4), with strike direction N145E, dip angle 85 and slip angle 85, while a slip and an area of faulting cannot be separately solved because of a trade-off between them.
(2) Hyper-resonance
At stations in the southern part of the Boso peninsular in azimuths of N145W to N150W, we saw a remarkable resonance of few cycles of SH waves of periods of 15 s to 20 s and amplitude of up to 1 m following the SH pulse, which we call hyper-resonance. It can be attributed to thick tertiary accretional layer.
(3) Dynamic trigger
Giant near-source seismic waves triggered activity of M6 or larger aftershocks in the source area. Those of a few hundred kPa triggered aftershock activity at active volcanoes such as Tateyama and Yakedake in the Hida mountains. These aftershock activity lowered around 50 minutes after the main shock. After one and half hours, two and half hours and three hours, the higher mode Rayleigh waves, the fundamental Love waves and the Rayleigh waves, respectively, of 200 s to 300 s of a few kPa returned back to Japanese Islands. They reactivated the aftershock activity.

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Bayesian inference of centroid moment tensors of the April 2016, Kumamoto (Kyushu, Japan), earthquake sequence

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On 2016 April 16, Kumamoto prefecture in Kyushu region, Japan, was devastated by a shallow M7.3 earthquake. The seismic activity in the region started by foreshocks 28 hours before the main shock. The series of foreshocks have origin in Hinagu fault zone intersecting the main event's Futagawa fault zone Hence, the tectonic background for this earthquake is rather complex.
We computed centroid moment tensors (CMTs) for 11 events with M between 4.8 and 6.5, using the strong motion records of K-NET, KiK-net and F-net networks. We used the innovative Bayesian full-waveform inversion, ISOLA-ObsPy, which takes into account uncertainty of the velocity model structure. Such approach allows us to assess uncertainty of the inverted moment tensors.
The moment tensors show significant spatial variations. Dip-slip events are connected to the N-S extensional tectonic regime and right-lateral strike-slip events are linked to the NE-SW shear zone (Median Tectonic Line). Strike-slip events located close to the intersection of Hinagu and Futagawa fault zone are dipping slightly to east, while those in the southern area (Hinagu fault zone) are dipping to west. Most of events contain only minor CLVD component, which is statistically insignificant and can be related to the velocity model uncertainty. Nevertheless, two of the CMTs involve significantly large CLVD component (~30%), which may reflect complex rupture process. Decomposition of those moment tensors into two pure-shear moment tensors is non-unique. Nevertheless, preserving T-axis of the decomposed moment tensors suggests combined right-lateral strike-slip and dip-slip mechanisms, which are consistent with the tectonic settings of the intersection of the Hinagu and Futagawa fault zones. Finally, the Bayesian full-waveform inversion of CMTs of the Kumamoto earthquake sequence demonstrates the abilities of such a methodology, and suggests complex tectonic background for this earthquake sequence.

Intraplate events off Sumatra – 3-D evolution

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The dominantly strike-slip Mw 7.8 event on 2016 March 2 occurred in the northwestern Wharton Basin in an area with no previously recorded large earthquake. Analysis of the higher-frequency energy radiation (> 0.25 Hz) as a function of time using a suite of global stations, with good azimuthal control, indicates that the event initiated on a nearly east-west fault and then the main energy release was on a conjugate north-south fault. High frequency radiation is emitted through the full thickness of the lithosphere in the main part of the event. Late energy emission comes from depth over a broader area suggesting minor failures at the base of the lithosphere.
A similar behaviour is seen for the 2000 June 18 much further away from the subduction zone. In each case the events occur in a region with slightly lower shear wavespeed than their surroundings, perhaps indicating weakness in the full lithosphere.

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Rupture evolution during the Mw 8.3 2015 Illapel Chile earthquake in relation to swarms

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A source model for the Mw 8.3 2015 Illapel Chile earthquake is constructed by using a broad frequency range of teleseismic P-waveforms recorded at globally distributed stations. A spatiotemporal slip distribution is obtained with the kinematic waveform inversion method taking into account the uncertainty of Green's function, and an evolution of high-frequency (HF: 0.3–2.0 Hz) radiation sources is tracked with the hybrid backprojection method, which resolves locations of the HF sources by stacking cross-correlation functions of the observed waveforms and theoretically calculated Green's functions.

The source model, in a gross sense, shows apparently slow, unilateral rupture propagation at < 2 km/s along the strike direction with the maximum slip about 10 m at around 70 km northwest of the epicenter, but in detail, the model involves two independent rupture episodes, both propagating up-dip and northward direction at variable rupture velocities (2–3 km/s) along the rupturing paths. The two rupture episodes are separated by the HF bursts occurred along the deeper (around 35 km depth) parts of the fault, which possibly triggers and accelerates the secondary rupture episode.

Secondary rupture evolves in a way to avoid the interplate swarms observed in 1997–1998 locating at the northern and the northeastern edges of the rupture area, and terminates without the intense HF radiation around the boundary between the source area and the swarm region. Less excitations of HF waves at rupture termination suggests the gradual deceleration of rupture, since HF waves are radiated when a rupture front abruptly accelerates or decelerates. The HF-deficient rupture termination may correspond to the frictional property or stress state around the boundary between the source area and the swarm region, which gradually transitions from the state governing megathrust rupture to that carrying the swarms driven by the aseismic slip.

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Rupture on the megasplay fault along the Nankai trough during the off-Mie earthquake (Mw=6.0) on 1 April 2016

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On 1 April 2016, a moderate-sized off-Mie earthquake (Mw=6.0) occurred off the Kii Peninsula, southwest of Japan. The epicenter is located updip of hypocenter of the 1944 Tonankai earthquake (Mw=8.2).
Wallace et al. (2016) obtained that this earthquake occurred along the plate boundary of the Nankai trough, but their hypocenter determination was based on a 1D velocity structure. Horizontal heterogeneity along the dip direction is not negligible in subduction zones.
We determined the hypocenters of the 2016 earthquake by using a 2D velocity structure considering the horizontal heterogeneity in the study area. We used P-wave arrival time at each DONET station deployed immediately above the source region (Kaneda et al., 2015; Kawaguchi et al., 2015). The mainshock was located at 9.7 km depth shallower than 11.4 km of Wallace et al. (2016). By comparing with a reflection profile obtained from a multichannel seismic survey (MCS), the mainshock is attributed to a slip along the megasplay fault rather than the plate boundary.
In the transition zone of the accretionary wedge between the megasplay fault and the plate boundary is characterized by a zone of low seismic-wave velocity consisting of fluid-rich sediments, which could not support strong shear stress to cause large earthquakes. Accordingly, it is difficult to cause large earthquakes along the megasplay fault or the plate boundary in the source region of the 2016 earthquake. Wallace et al. (2016) attributed this earthquake to a slip along an unstable patch in conditionally stable zone of the plate boundary, but its geological meaning has not been clarified yet.
In MCS profiles, we can recognize locally very weak reflections along the megasplay fault or the plate boundary around the mainshock source, which we consider as an unstable patch because of the low impedance contrast. We hypothesize that fragments of seamounts, of which the main body has been subducted to deeper part, form the strong patch in the sediments.

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Asperity imaging of the ML6.0 2016 Amatrice, Italy, earthquake from dynamic rupture simulation

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Several damaging earthquakes of magnitude 5.5 – 6.4 have occurred in the Central Italy since August 24th 2016. The earthquakes show normal faulting mechanisms, coherent with the formation of regional tectonics surrounding the Apennine Mountain. We aim to characterize dynamic source parameters (asperity distribution) from the dynamic rupture and wave propagation simulations, firstly for the ML6.0 August 24th 2016 earthquake. We hypothesis that fault heterogeneity is represented by a combination of circular patches of asperity and determine their physical parameters. We apply the boundary domain method combining boundary integral equation and finite difference schemes. The calculation is still too expensive to run systematic inversion process, but the simulations indicate a better combination of the dynamic rupture parameters, in terms of patch dimension, location and frictional parameters. When focusing on one of the nearest ground motion record of Amatrice (epicentral distance of about 10 km), a single patch toward up-dip and strike directions between the hypocenter and this station is suggested. Its dimension is not larger than a radius of 4 km and static/dynamic stress drops of 4 and 6 MPa or more, respectively.

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Dynamic Rupture Simulations Constrained by Experimental Data to Investigate the Fault Behavior of Mega-Thrust Earthquakes

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The investigation of dynamic rupture propagation is very important to understand the seismic behavior of mega-thrust earthquakes such as the 2011 Tohoku earthquake. The shallow parts of the fault (near the trench) hosted large slip and long period seismic wave radiation, whereas the deep parts of the rupture (near the coast) hosted smaller slip and strong radiation of short period seismic waves. Understanding such depth-dependent feature of the rupture process of the Tohoku earthquake is necessary as it may occur during future mega-thrust earthquakes in this and other regions. In order to achieve such understanding, dynamic rupture modeling is an important tool (e.g., Galvez et al., 2014). By incorporating the results of laboratory studies of samples of fault materials collected from plate boundary fault zones, such as the Japan Trench, dynamic rupture simulations can be made more realistic.
In this study, we developed dynamic rupture models of the Tohoku earthquake based on initial conditions and fault strength properties constrained by results of experimental studies (Hirono et al., 2016). Our large-scale simulation used the 3D spectral element method on unstructured grids (Galvez et al., 2014) with performance tunning for the Earth Simulator at JAMSTEC.
Our model reproduced the depth-dependency of the rupture process of the Tohoku earthquake. We also examine the sensitivity of the results to model parameters and assumptions, for instance to the value of the slip weakening distance (Dc). We find that the value of Dc does not affect the final slip distribution, as long as it is small enough to allow the rupture to develop and propagate to the trench. A long Dc (order of 10 m) is reasonable in terms of fracture energy and promotes the generation of long period seismic waves on the shallow part of the fault.

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Super-shear fault rupture propagation during the 2016 Kumamoto earthquake (Mw7.1); Possible implication for fault strength

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I investigated the fault rupture process of the April 16, 2016 Kumamoto earthquake, using a seismic back-projection methodology (Pulido et al. 2008, Pulido 2016), and a dense array of near-source strong motion records from the K-NET/KiKnet networks. I selected all the KNET/KiKnet records of the mainshock within 100 km around the Hinet epicenter, and used the fault-parallel component rotated from the horizontal components. I bandbass filtered the data between 5 to 10 Hz and calculated the envelopes of velocity time series. Envelopes were stacked within a horizontal grid mesh covering the regions around the Hinagu and Futagawa fault traces and beyond, to obtain a temporal and spatial image of rupture propagation. My back-projection results show that significant grid energy was released in a region spanning 43km length along the Hinagu (16km) and Futagawa (27 km) fault zones. Back-projection results show a bilateral fault rupture propagation along the Hinagu and Futagawa faults, characterized by a slow sub-Rayleigh rupture velocity of 1.4 ~ 1.7 km/s, for the first 5.5 seconds of imaged rupture (4~9.5s from the origin time, OT). The rupture propagation towards the NE (along the Futagawa fault) experienced a very rapid increase in rupture velocity by reaching a value ~1.4 times larger than the average S-wave velocity (Vrup= 4.7 km/s) at 9.5s from OT, and remained super-shear for approximately 4.5 s (9.5 ~14s from OT) until fault rupture arrest. I also imaged a clear sub-Rayleigh rupture propagation towards the SW along the Hinagu fault zone (Vrup= 3.1 km/s), from 11 to 14 seconds after OT. My results indicate a super-shear transition length L~10 km, which is approximately 5 times the typical value of the nucleation zone size (Lc) for a Mw7.1 earthquake. These results may imply a low fault strength value S.

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Why did the moderate size 2010 Yushun, China earthquake (Mw=6.8) produce supershear rupture?

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Owing to supershear ruptures, seismic hazards in the 2010 Yushu, China earthquake(Mw=6.8) is particularly severe. So far, the mechanism remains unclear. To this end, we construct finite element model based on the actual geometry of the seismogenic fault in the earthquake. In the model, the fault consists of two segments, and there is an intersection angle of 10º between them, forming fault bent. The simulation result shows that the main rupture for the Yushu event is composed of two sub-events. Once the rupture was nucleated at the hypocenter, the rupture first propagated along the first fault segment at speed of subshear wave velocity. When the rupture goes over the fault bent, the rupture speed turned into supershear wave velocity immediately along the second fault segment. Moreover, the calculation results suggest that dislocations at fault surface, seismic wave speed and strong ground motion acceleration are largely amplified by supershear ruptures, giving rise to terrible damage. This may be an important reason why severe seismic damage was caused in the Yushu earthquake. In particular, we can see from numerical experiment that rupture speed would not change if the strike of the fault in the model does not bend in the case in which all other model parameters keep unchanged. However, if the intersection angle between the orientation of initial stress and the fault varies, rupture will not necessarily propagate at supershear wave speed, even if there is a fault turning in the fault system. Only if the relationship between the orientation of initial stress and the strike of the fault is just perfect, the fault bent possibly promotes supershear ruptures. Thuse, supershear rupture occurred in the Yushu event may be resulted from optimum state in which perfect relationship between orientations of initial stress and the strike of seismogenic fault is formed. It is presumably one of the reasons why natural earthquakes with supershere ruptures are rarely seen.

Dynamic Source Inversion of Intermediate Depth Earthquakes in Mexico

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The source mechanisms of earthquakes at intermediate depth (50-300 km) are still under debate. Due to the high confining pressure at depths below 50 km, rocks ought to deform by ductile flow rather than brittle failure. Several source mechanisms have been proposed, but for neither of them conclusive evidence has been found. One viable mechanism is Dehydration Embrittlement, where liberation of water lowers the effective pressure and enables brittle fracture. Another is Thermal Runaway, a highly localized ductile deformation. In the Mexican subduction zone, intermediate depth earthquakes represent a real hazard in central Mexico due to their proximity to highly populated areas and the large ground accelerations.

To improve our understanding of these rupture processes, we use a recently introduced inversion method to analyze several intermediate depth earthquakes in Mexico. The method inverts strong motion seismograms to determine the dynamic source parameters based on a genetic algorithm. It has been successfully used for the M6.5 Zumpango earthquake (62 km depth). For this event, high radiated energy, low radiation efficiency and low rupture velocity were determined. This indicates a highly dissipative rupture process, suggesting that Thermal Runaway could probably be the dominant source process.

In this work we improved the inversion method by introducing a theoretical consideration for the nucleation process that minimizes the effects of rupture initiation and guarantees self-sustained rupture propagation. Preliminary results indicate that intermediate depth earthquakes in central Mexico may vary in their rupture process. For instance, for a M5.9 earthquake at 55 km depth that produced very high accelerations in Mexico City we found a moderate radiation efficiency and a typical rupture velocity. Differences and similarities between the earthquakes studied here will help to better elucidate the physical processes originating intermediate depth earthquakes.

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Slip-weakening distance and strength drop inferred from near-fault deformation during the 2016 M7.8 Kaikoura earthquake

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The 2016 M7.8 Kaikoura (New Zealand) earthquake struck the east coast of the northern South Island, resulting in large surface offsets (>10 m), numerous landslides, extreme surface ground motions (over 1g), a regional tsunami, and large-scale slow slip events on the Hikurangi subduction interface. Since the earthquake was well recorded by GeoNet strong motion and GPS networks, near-fault ground motion may provide direct measurements of dynamic parameters associated with the fault-weakening process. Here we estimate a proxy of slip-weakening distance Dc'', defined as double the fault-parallel displacement at the time of peak ground velocity, from accelerograms recorded at near-fault stations. Three-component ground displacements were recovered from the double numerical integration of accelerograms, and the corresponding static displacements are validated against those derived from InSAR data. We estimate Dc'' of about 5 m at KEKS station located at 2.7 km from a segment of the Kekerengu fault where a surface offset of more than 10 m has been found. The inferred Dc'' is the largest value ever estimated from near-fault strong motion data, yet appears to follow the scaling of Dc'' with final slip reported in previous studies. The corresponding slip-weakening distance Dc and strength drop on the same fault segment may be validated against dynamic rupture simulations.

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Photoelastic Study of Dynamic Stress Transfers in Granular Media

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In our earlier study (JpGU Meet. 2008, AGU Fall Meet. 2009), using a high-speed camera, we conducted fully-controlled laboratory experiments associated with large dynamic deformation of granular materials that may be observed, e.g. in earthquake faulting and landslides. Especially, as a fundamental investigation, our attention was paid to transient granular mass flow from a (semi-)cylindrical column consisting of dry granular materials (glass beads). We traced the particle movement and development of slip lines inside the granular column that was set on a rigid horizontal plane and collapsing due to the action of gravity, and showed, for instance, the influence of frictional properties of the horizontal plane and beads on the average flow velocity and the final shape of the collapsed column. However, the details of stress transfers in granular media subjected to such dynamic deformation have not been well clarified yet. Therefore, here, as a preliminary observation for deeper understanding of stress transfers and propagation of waves and rupture inside granular media, experimental technique of dynamic photoelasticity is used. Penny-shaped photoelastic particles (diameter 20 or 40 mm) made of epoxy resin are prepared and placed on a rigid horizontal plane, and dynamic impact is given to a particle by a gun-launched projectile (impact velocity 50-80 m/s) or by another free-falling photoelastic particle (impact velocity 2-3 m/s). The transient stress transfers are recorded by a high-speed camera at a frame rate of up to 100,000 fps. In a single particle system, where only one particle is situated on the plane, dynamic wave propagation is recognized inside that single particle, but in a layered multi-particle system stress is transferred quasi-statically from a particle to neighboring ones and wave propagation is not clearly identified. This may suggest preloading (and more static contact between each particle) is needed for visualization of waves in the layered system.

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Near-fault Tilt Motion and Conjugate Faulting

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There have been reports of conjugate faults that have ruptured during earthquakes. However, it is still unclear whether or not these conjugate faults ruptured coseismically during earthquakes. In this paper, we investigated near-fault ground tilt motions observed at the IWTH25 station during the 2008 Iwate-Miyagi Nairiku earthquake (Mw 6.9). Since near-fault tilt motion is very sensitive to the fault geometry on which the slip occurs during an earthquake, these data make it possible to distinguish between the main fault rupture and a rupture on the conjugate fault. We examined several fault models that have already been proposed and confirmed that only the models with a conjugated fault could explain the tilt data observed at IWTH25. The results support the existence of simultaneous conjugate faulting during the main rupture. This will contribute to the understanding of earthquake rupture dynamics because the conjugate rupture releases the same shear strain as that released on the main fault, and thus it has been considered quite difficult for both ruptures to accelerate simultaneously.

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Supershear rupture induced by step over geometry and its effect on near field ground motion

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Based on dynamic rupture simulations on step overs, we show that rupture speeds can jump to supershear speed on the secondary fault of a step over in a 3D full-space after re-nucleation, whose initial shear stress preclude such a supershear transition according to the Burridge-Andrews mechanism, and the rupture speed on the primary fault is sub-Rayleigh. The low normal stress zone and the high shear stress zone beyond the fault step, which radiate from the end of the primary fault if its rupture arrest is sudden, determine the supershear rupture occurrence on the secondary fault. However, a low shear stress zone traveling at the shear wave speed is also radiated, making the rupture speed return to subshear in most cases. Sustained supershear ruptures on the secondary fault are also possible on compressional step overs under certain conditions. Self-arresting phenomenon are observed in the overlapped area on the secondary fault. In a half-space model where supershear rupture is induced by the free surface on the primary fault, the rupture speed on the secondary fault rapidly transits to subshear near the fault step if its width exceeds a critical value. We further calculate near-field ground motions of the half-space cases to understand its high frequency radiation pattern.

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Modeling dynamic earthquake rupture with coseismic off-fault damage

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Off-fault stress concentration induced by dynamic earthquake ruptures can generate coseismic off-fault damage, which has an effect on source mechanisms of earthquakes. We need continuum-discontinuum analysis to understand the process of generating the off-fault damage in a brittle material surrounding faults and the role of it in the source mechanisms and seismic wave radiation.

In this study, we adopt combined finite-discrete element method (FDEM), which can model real cracks in off-fault fields generated during the dynamic earthquake ruptures. The advantage of FDEM is that it can handle a wide range of length scales, from metric to kilometric scale, corresponding to the off-fault damage and the main fault respectively. Every potential failure plane in the medium follows a cohesive law (in tension and in shear). The main fault is assumed to follow a linear slip-weakening friction. Thus we can have an estimate of fracture energy dissipated on the main fault and the off-fault damage separately. We used the FDEM-based software tool called HOSSedu (Hybrid Optimization Software Suite - Educational Version), which was developed by Los Alamos National Laboratory.

We firstly demonstrated the cross-validation of the FDEM tool for modeling earthquake ruptures with other conventional numerical schemes like spectral element method and boundary integral equation method to evaluate the accuracy with various element sizes and artificial viscous damping factors. We then modeled earthquake ruptures allowing for the coseismic off-fault damage with appropriate fracture nucleation and growth criteria. It shows that high-frequency radiation is enhanced by the dynamically generated off-fault damage. The orientation of maximum compressive principal stress of the pre-stress field with the main fault plays a role in generating the off-fault damage such that the dynamic off-fault damage is more likely to occur on the extensional side of the main fault for high principal stress orientation.

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Investigating the variability of near-source ground motions using pseudo-dynamic source models at the SCEC Broadband Platform

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The accurate prediction of ground motion intensity and variability is a critical element in seismic hazard assessment. Especially it is important to note that the variability of ground motions plays an important role in probabilistic seismic hazard analysis (PSHA) since the exceedance probability of ground motions is taken into account. Physics-based source and ground motion modeling has become popular, given advanced earthquake rupture and wave propagation modeling schemes and fast growing computing capability. There have been intensive community efforts to construct a physics-based broadband ground motion simulation platform, supported by the Southern California Earthquake Center (SCEC). Using various pseudo-dynamic source models at the SCEC broadband platform, I investigated the variability of near-source ground motions. Preliminary results show that the variability of low frequency ground motions is relatively compatible with the variability of empirical ground motion prediction equations (GMPEs) while the variability of high frequency ground motions is not. We may need to pay more attention to the variability of ground motions by considering the variability of input models when we construct a physics-based ground motion simulation platform.

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Variation of Earthquake Source Scenarios along the Nankai Trough for Hazard and Risk Assessment

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Historical Nankai Trough earthquakes show a large variation of source characteristics. Recent new observations reveal the diversity of earthquake sequence not limited to the coseismic rupture and segmentation. As a framework of the core-to-core collaborative research program of Earthquake Research Institute, the University of Tokyo and Disaster Prevention Research Institute, Kyoto University, we construct earthquake source scenarios along the Nankai Trough. To show the variation of scenario earthquakes, the logic tree is established based on expert opinions of geodesy, crustal structure from offshore to onshore regions, seismicity, and history for seismic and tsunami hazard assessment and related risk. The distributions of slip deficit, seamount, fault branch, slow earthquake, repeating earthquake, seismicity, and historical earthquake and tsunami source information are integrated with a weight ranging from 0 to 100%. The magnitude potential is controlled by the idea of partially coupled regions (Loveless and Meade, 2015) as a function of the coupling rate as well as overlaying the expert opinions. We validate seismic intensity and long-period ground motions for seismic hazard, and tsunami height and inundation area for tsunami hazard. The seismic and tsunami risk is assessed by population density, social and economic impact along the Pacific Ocean belt, and locations of nuclear and thermal power plants from the viewpoint of social science. We investigate the factor analyses to link the above mentioned earthquake scenarios, hazard, and risk.

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A web-platform benchmark for moment tensor inversion

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Moment tensor inversion is a powerful tool for the determination of the earthquake source parameters. Following extensive developments in the last two decades, global and regional moment tensor services are nowadays becoming a standard and a growing number of different moment tensor catalogs are provided to the community. In parallel, a wide range of software offering standard moment tensor tools are available to seismologists. However, moment tensor results are highly affected by data pre-processing, data selection and implemented methodologies. As a result, moment tensor catalogs often show systematic differences among source parameters. Thus, despite of the widespread diffusion of data and methods, moment tensor data mining faces new challenges. In response to these problematic, a IASPEI working group (WG) on routine moment tensor inversion was started, with the main aim of developing and implementing a benchmark and verification platform for moment tensor inversion procedures, and to provide recommendations for the scientific community. We present a preliminary web-based platform, where new moment tensor inversion methods can be tested and young researchers new to the field can find and use the benchmark to test their own developments over a broad range of applications. The platform provides access to ground truth events representative of a broad type of seismicity and monitoring conditions, including synthetic and real datasets.

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Centroid moment tensor solution using 3D heterogeneous anisotropic Earth: application to Papua New Guinea and Solomon Islands

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Moment tensor (MT) representation of the earthquake source is well established and is being routinely calculated on a global scale by Global-centroid moment tensor project (GCMT). Routine calculation of MT is usually done using Green's functions calculated from a 1D layered Earth velocity structure. Here, we have calculated CMTs for 318 events with Mw > 5.0 occurred in Papua New Guinea and Solomon Islands during 2006 - 2016 using a continental scale 3D heterogeneous upper-mantle velocity structure model, AMSAN19 (Fichtner et al. 2009). Our solutions show considerable differences in comparison to GCMT. The most prominent difference is in double-couple (DC) percentage which shows a significant increase. We also observe differences in strike, dip and rake angles of the DC part of MT, which provides new insight into the tectonics of the region. The resolution in centroid depth has increased specifically for shallow events (depth < 25 km) and our new centroids shed light on dipping structures at the New Guinea Trench. The new CMT solutions obtained using the 3D model are superior to those using the spherically-symmetric models of the Earth, which is evident in the data fit increase of about 30%.
We have shown the feasibility of using a 3D velocity model on the continental scale to improve the recovery of depth, location and MT components for shallow events, which opens new avenues to more reliable tectonic interpretations and hazard assessments. Our library of synthetic seismograms will be used at Geoscience Australia to supplement existing tools for moment tensor inversion.

Reference:
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Single Layer Recurrent Neural Network for detection of swarm-like earthquakes in West Bohemia and South-west Iceland

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We present a new method of local event detection based on neural networks. The proposed algorithm uses a unique neural network architecture. It combines features used in other neural network concepts like Real Time Recurrent Network and Nonlinear Autoregressive Neural Network to achieve a good detection performance. We use the recurrence combined with various delays applied to recurrent inputs to make the network remember history of many samples - the Single Layer Recurrent Neural Network (SLRNN). The network was first trained and tested on data from local seismic network in West Bohemia (Webnet). Then we applied the trained network to different dataset from local seismic network in South-west Iceland (Reykjanet). Both networks monitor earthquake swarm areas, both networks have similar number of stations used for detection and both cover roughly equal areas. We show that the neural network trained on Webnet data could be used on Reykjanet data with satisfactory results.

An evolutive quasi-real-time source inversion based on a linear inverse formulation

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Finite source inversion is a steppingstone to unveil earthquake rupture. Significant progress has been made on approaches regarding earthquake imaging, thanks to new data acquisition and methodological advances. However, most of these techniques are posterior procedures once seismograms are available. Incorporating source parameters estimation into early warning systems would require to update the source build-up while recording data.

We developed a kinematic source inversion formulated in the time-domain, for which seismograms are linearly related to the slip distribution on the fault through convolutions with Green functions previously estimated and stored. These convolutions are performed in the time-domain as we progressively increase the time window of records at each station specifically. Selected unknowns are the spatio-temporal slip-rate distribution to keep the linearity of the forward problem with respect to unknowns. Through the spatial extension of the expected rupture zone, we progressively build-up the slip-rate when adding new data by assuming rupture causality.

This formulation is based on the adjoint-state method for efficiency. The inverse problem is non-unique and, in most cases, underdetermined. While standard regularization terms are used for stabilizing the inversion, we avoid strategies based on parameter reduction leading to an unwanted non-linear relationship between parameters and seismograms for our progressive build-up. Rise time, rupture velocity and other quantities can be extracted later on as attributes from the slip-rate inversion we perform.

Satisfactory results are obtained on a synthetic example proposed by the Source Inversion Validation project (Mai et al. 2011). The application of this method to the Kumamoto 2016 earthquake is currently being explored. Our specific formulation combined with simple prior information, as well as numerical results obtained so far, yields interesting perspectives for a quasi-real-time implementation.

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Source properties of large earthquakes in subduction zones using 3D heterogeneous Earth: application to the Australasian region

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Revealing earthquake source complexity, rupture process and the source time function of large earthquakes is an important aspect of earthquake seismology. A significant number of researchers have investigated these properties using 1D (spherically symmetric) Earth models. Using a similar approach, we first investigated 10 selected large earthquakes with moment magnitudes exceeding 7.8 in the Australasia region, occurred in Papua New Guinea, Solomon Islands, Tonga-Fiji and New Zealand. Acknowledging that seismic records contain the complexities from both source and Earth structure, we explore a hypothesis that a simple, spherically symmetric Earth structure introduces spurious effects into the source parameters. We use 3D heterogeneous upper-mantle velocity structure and create synthetic data for scenarios that encompass complex ruptures and source time functions (at periods 40 – 200s). We then invert for the source parameters such as moment tensor, source time function and location using these synthetic data in both 1D and 3D Earth. We confirm that the source complexity can act as a compensation for the incomplete knowledge of Earth structure. Consequently, we calculate the source time function of the selected large earthquakes from the Australasian region in 3D Earth and discuss our findings. We also consider the source directivity for large earthquakes as one of the target parameters.

*S13-P-06
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Complete synthetic seismograms based on a spherical self-gravitating Earth model with an atmosphere-ocean-mantle-core structure

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A hybrid method is proposed to calculate complete synthetic seismograms based on a spherically symmetric and self-gravitating Earth with a multi-layered structure of atmosphere, ocean, mantle, liquid core and solid core. For large wavelengths, a numerical scheme is used to solve the geodynamic boundary-value problem without any approximation on the deformation and gravity coupling. With the decreasing wavelength, the gravity effect on the deformation becomes negligible and the analytical propagator scheme can be used. Many useful approaches are used to overcome the numerical problems that may arise in both analytical and numerical schemes. Some of these approaches have been established in the seismological community and the others are developed for the first time. Based on the stable and efficient hybrid algorithm, an all-in-one code QSSP is implemented to cover the complete spectrum of seismological interests. The performance of the code is demonstrated by various tests including the curvature effect on teleseismic body and surface waves, the appearance of multiple reflected, teleseismic core phases, the gravity effect on long period surface waves and free oscillations, the simulation of near-field displacement seismograms with the static offset, the coupling of tsunami and infrasound waves, and free oscillations of the solid Earth, the atmosphere and the ocean. QSSP is open source software that can be used as a stand-alone FORTRAN code or may be applied in combination with a Python toolbox to calculate and handle Green's function databases for efficient coding of source inversion problems.

*S13-P-07
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Detecting the Temporal Variation in Seismic Velocity Accompanied by 2011 Tohoku-Oki Earthquake and the Slow Slip Event, Using Seismic Interferometry of Ambient Noise

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Between the end of January and the occurrence of the largest foreshock on March 9 that preceded the 2011 Tohoku-Oki earthquake, slow slip events and low-frequency tremors were detected off Miyagi (Ito et al., 2013, 2015; Katakami et al., 2016). We apply seismic interferometry using ambient noise to data from 17 OBSs that were installed above the focal region before the earthquake. All OBSs with three components are short-period seismometers with an eigenfrequency of 4.5 Hz that were deployed between November 2010 and April 2011.
The method is as follows. First, we applied a band-pass filter of 0.25-2.0Hz and a one-bit technique. Second, we calculated Auto-Correlation Coefficients using a 5-s time window with lag time from -30 s to 30 s at intervals of 0.1 s, using seven continuous days of waveforms to make a daily ACF. Third, we stacked up all daily ACFs for the entire time period, to make a reference ACF. Finally, we calculated the Correlation Coefficients between the one-day ACF or the 16-day ACF and the reference ACF.
The primary results are follows. At all OBSs, the 16 days' CC declined after the SSE initiated and then it recovered in the latter half of the SSE duration. In the region of SSE occurrence, the difference between the absolute and incremental reduction in the 16 days' CC is small. However, in the area of the largest foreshock, the difference is significant. The former 16 days' CC values are suddenly decreasing before the SSE, and the latter 16 days' CC values are gradually decreasing starting around November, or around four months before the largest foreshock. The small difference could be related to the occurrence of SSE, while the large difference could be related to critical conditions preceding the largest foreshock.

*S13-P-08
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Rupture process of the Ms 7.4 November 15, 2004 Colombia earthquake

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The subduction zone in the northwestern part of the South American plate presents a complex tectonic process due to the interaction between the Nazca, Cocos and Caribbean plates. Analyzing the rupture process in this region is of great importance to understand the occurrence of seismic events in Colombia. We have determined the space-time distribution of the slip on the fault plane for the November 15th, 2004 earthquake, located in the Colombian-Ecuadorian trench in the Colombian Pacific subduction zone. This event is one of the most shallow and significant in recent years because it occurred in the region where the largest earthquakes have been reported such as the 1906 (Mw=8.8), 1942 (7.9), 1958 (Mw=7.8) and the 1979 (Mw=8.2). We applied the inversion method developed by Yagi et al. (2003) using the P waveform modeling at teleseismic distances, which is a numerical method that calculates the slip distribution on the fault plane assuming a seismic source as a sequence of point sources. The slip distribution obtained is the one that best retrieves the observed records in several teleseismic stations. The parameters that best fit to describe the process of rupture of this event were: strike= 177, dip= 79, slip= 85, depth h = 15 km. The rupture process obtained indicates that the rupture propagates towards the surface with a maximum slip of 3.7 m at depth of 15 km. The temporal function for this event shows a complex rupture with two peaks and a total duration of 15 seconds.

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Source inversion and stochastic ground motion modelling of the August Mw 6.8 Myanmar earthquake

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An intermediate-depth Mw 6.8 earthquake struck Myanmar on 24 August 2016. This earthquake was felt throughout the country and caused some damage in the Chauk and Bagan areas. USGS reported the earthquake mechanism as a reverse fault (Strike1: 166, Dip1: 83, Rake1: 89 and Strike2: 356, Dip2: 7, Rake2: 100), which would be cutting the subducting slab near vertically or near horizontally. There has been no previous intermediate depth earthquake with a similar mechanism in the Myanmar region from available moment tensor catalogs. We study the earthquake source mechanism and slip distribution using teleseismic body-wave inversion implemented in the Kikuchi-Kanamori code. We used 33 P- and 34 SH-waves data from stations at teleseismic distances (30º to 90 º). Testing different earthquake depths during the inversion, we found the lowest variance at 85 km depth. We set the fault plane size to 35 x 35 km2 and divided into a 5 km grid. We obtained a similar earthquake mechanism to the USGS result, i.e. reverse faulting event (Strike1: 165, dip1: 82, rake1: 97 and Strike2: 303, Dip2: 11, Rake2: 49). Regarding the slip distribution, we note that the maximum slip is 0.9 m and is located at the down-dip edge of the fault plane. This earthquake occurred within the subducting Indian-plate indicating slab parallel tension. We applied stochastic finite-fault ground-motion simulation based on a dynamic corner frequency to simulate the ground motion for this event. The results were compared to seven strong motion stations in the Myanmar region to validate our simulated values. The closest recording was made ˜50 km from the epicenter. The damage reported by the Department of Meteorology and Hydrology of Myanmar is consistent with the relatively high ground motion.

*S13-P-10
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Early rupture process of the 2016 Kumamoto earthquake inferred from source imaging

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The 2016 Kumamoto earthquake (Mj 7.3) occurred in Kumamoto prefecture, Japan, on 16 April 2016 (JST). The source region includes the Futagawa fault and northern part of the Hinagu fault. In this study, we investigate the early rupture process during 2.5 seconds after the origin time by source imaging technique (Takenaka et al., 2009, EPS). We use P-wave portion on vertical components of waveform records at 40 seismic stations from the seismic networks of JMA, NIED and Kyushu University. We assume three fault segments: first one (segment 0) is the plane of strike N100E and dip 71 degrees passing the hypocenter by JMA focal mechanism; second one (segment 1) is the plane of strike N205E and dip 72 degrees for northern part of the Hinagu fault estimated by GSI; third one (segment 2) is the plane of strike N235E and dip 60 degrees for the Futagawa fault inferred by GSI. In the result of source imaging on these segments, we found several characteristic slip region. On segment 0, the rupture initiated and propagated. Then, at after 0.5 seconds from the origin time, relatively larger slip appeared on the intersection line with segment 1, and the rupture transferred to segment 1. On segment 1, we found two strong slip regions: at southwest side of the segment after 2.0 seconds from the initial break; at near the shallower part of the intersection line with segment 2 after 2.3 seconds from the origin time. The latter slip shows that the rupture did not overcome the intersection line with segment 2. This feature suggests that the shallower part of the junction with segment 2 worked as a barrier at the stage of initial rupture and the rupture might have transfer to segment 2 from deeper part of the junction at the later stage.

*S13-P-11
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Source imaging of the 2016 Kumamoto earthquake by back-projection of near-filed P wave records.

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The direction and the speed at which fault rupture proceeds, as is well known, controls major feature of ground motion around the causal faults. However, heterogeneous rupture process has been only partially taken into account in the current framework of strong ground motion prediction.
For more realistic and precise strong ground motion calculation, slip velocity function and rupture velocity variable on fault planes are expected to be take into consideration in the future. Actually, some attempts to incorporate such heterogeneity for ground motion prediction are under way in the world. In pursuing the goal, accumulation of information on fault rupturing process is essential to constitute a heterogeneous source model.
In this study, I applied back-projection technique to reveal the time history of seismic wave emission during the Kumamoto earthquake. Strong motion records recorded at 27 KiK-net and K-NET stations within 100km hyopocentral distance were used. Traveltime data were processed in the similar way as Takenaka and Yamamoto(2004) to obtain seismic emission image with more precision in relative location. The back-projection technique used in this study is similar to that by Kao and Shan(2004), and Ishii et al.(2005).
As a result, clear image of rupture propagation from Takano-Shirahata segment of the Hinagu fault zone to Futagawa segment of the Futagawa fault zone was obtained, where the strike and the dip of those two fault planes are different. The rupture rapidly increased its seismic wave emission while it's moving toward northeast.
However, both the accuracy and resolution of the present results still leave plenty of scope for improvement. In the future study, I am planning to scrutinize data and data processing techniques, such as traveltime data and waveform stacking methods, to get more exact and high-resolution image of the source process.

Acknowledgement: I would like to express my gratitude to NIED for providing me with KiK-net and K-NET data.

*S13-P-12
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The intraplate Maranhao earthquake of 2017 Jan 03, northern Brazil: evidence of uniform regional stresses along the Brazilian equatorial margin.

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Lithospheric stresses in intraplate regions can be characterized by many different wavelengths. In some areas stresses vary over short distances of less than ~100 km, but in other regions uniform stresses can recognized for more than ~1000 km or so. However, not all intraplate regions are well sampled with stress measurements to allow a good characterization of the lithospheric stresses. On January 3, 2017, a magnitude 4 mb earthquake occurred near the equatorial coast of the Maranhao State, an aseismic area of northern Brazil. Despite the few permanent stations in northern Brazil, a well-constrained strike-slip mechanism was obtained from regional moment-tensor inversion. A detailed analysis of the back-azimuths of tens of aftershocks recorded by the closest station (40 km away) allowed the identification of the fault plane to be the NNW-SSE trending nodal plane. An estimate of the rupture length, about 1 to 2 km, was also possible. The strike-slip mechanism has coast-parallel P axis and coast-perpendicular T axis, in agreement with most of the focal mechanisms found further to the East. The coast parallel P axis is also similar to the SHmax measurements from breakouts further along the coast. The Maranhao earthquake fills an important gap of stress indicators in northern Brazil and suggests that the intraplate stress field is uniform along the 2000 km long northern coast. In addition, this event can be used as a test for detectability of the global IMS system, as it was not reported in the NEIC-USGS catalogue.

*S13-P-13
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Radiation Efficiency of Intraslab Earthquakes beneath Kyushu

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Although earthquakes in some subduction zones occur down to a depth of ~690 km, earthquakes in Kyushu are limited to a depth of ~200 km. As the Philippine Sea (PHS) slab is aseismically subducting to a depth of >400 km (Huang et al. 2013), physical properties in the PHS slab that control the genesis of intraslab earthquakes may change around a depth of ~200 km. This study estimates radiated energy and radiation efficiency for earthquakes that occurred at depths of 60-200 km beneath Kyushu, and discusses the depth variation in radiation efficiency.
To obtain reliable stress drop and radiated energy, we need to precisely estimate corner frequency of earthquakes from amplitude spectra. However, there is a strong trade-off between the corner frequency and quality factor, and so it is difficult to determine the two parameters accurately. Therefore, the corner frequency is first estimated by the coda wave spectral ratio method, and then the static stress drop and the quality factor are obtained from the shape of amplitude spectra for S waves using the pre-estimated corner frequency.
The obtained results show that the radiation efficiency does not show a depth dependency and the average value of the radiation efficiency is ~0.1, which is relatively small compared to those observed in the Pacific slab beneath Tohoku and Hokkaido. We infer that the small value of the radiation efficiency is due to high slab temperature in Kyushu.

*S13-P-14
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Source time function archive of deep earthquake: re-examination of hierarchy source model

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Rupture evolution process to large earthquake from its initiation is still hot topics in seismology. Many analysis and seismograms of major earthquakes show complexity of source process resulting from heterogeneous slip distribution on source fault and its time history. Smaller earthquake generally shows apparent simple rupture process. As one model to explain source evolution and size relation for smaller and large earthquake, hierarchy model was proposed (e.g. Fukao and Furumoto, 1985). In this study, we review last 20 years broadband seismograms excited by world-wide deep earthquakes and re-evaluate evolution model of rupture process.
Moment rate function of large size earthquake generally shows complexity of rupture process. As for shallow earthquake, body wave inversion are required including realistic earth's shallow structure model to get source time function. Meanwhile moment rate function of deep earthquake is obtained relative easily and stably using P-wave form. By global seismic network, world-wide deep earthquakes are recorded in homogenous sensitivity and station coverage.
From earthquake catalogue, recent 20 years deep seismic events are searched and applied grouping in hypocenters' area. From our broadband seismogram data base, we archived P wave waveforms that their magnitude is greater than 4.5. According to attenuation of seismic wave, source duration time of less than 2sec is undetectable. Source time functions of magnitude 5 class events are simple pulse functions. Around magnitude 6 to 6.5 events show also pulse shape function with significant width. Larger quakes than magnitude 6.6 have multiple functions in general and sometimes preceding to initial rupture process. Based on hierarchy model, it seems that an earthquake size locates on step between two hierarchy levels. Swarm-like deep earthquake sources also could be discussed about smaller scale heterogenous occuurece field in this presentation.

*S13-P-15
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A model of dynamic earthquake triggering based on rate- and state-dependent friction law

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Dieterich (1994) represented time to instability as a function of slip velocity assuming single spring-block system based on rate- and state-dependent friction law (RSF), and denoted that increase of the slip velocity due to static stress change triggers earthquakes. We extend this model to the case of dynamic stress change, noting that increment of logarithm of slip velocity is proportional to difference between static stress change and state variable (frictional strength) change. When fault strength is decreased by dynamic stress change due to seismic waves, earthquake occurrence could be advanced, resulting in delayed dynamic triggering even if no static stress change occurs.
We conducted numerical simulations of earthquake triggering assuming a circular asperity obeying RSF law revised by Nagata et al. (2012). In a situation where earthquakes repeatedly occur, we apply dynamic stress disturbance of sinusoidal variation at a certain time. The dynamic stress change causes increase of slip velocity following the RSF law, and resultant slip weakens the frictional strength. This leads to dynamic earthquake triggering depending on the amplitude of the disturbance. When the stress disturbance is sufficiently large, earthquake occurs during the period of stress oscillating. This might correspond to dynamic triggered earthquakes during passage of seismic waves. When static stress is also increased, smaller dynamic disturbance can trigger earthquakes with a shorter delay. Even if static stress change is negative, a certain amplitude of dynamic stress change can trigger earthquakes.

*S13-P-16
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Estimation of the dynamic rupture parameters for the 2016 Tottoriken-chubu earthquake

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We performed dynamic rupture simulations for the 2016 Tottoriken-chubu earthquake (M6.6). We used a boundary integral equation method, and supposed slip-weakening law as a frictional constitutive law. We assumed a vertical rectangular fault plane whose depth of the upper edge is 0.5 km, and the fault size is 19.5 km (strike) and 18 km (dip). We attempted to obtain spatial distributions of initial stress and critical slip weakening distance (hereafter referred to as Dc), which can fit better the slip distribution obtained from an inversion analysis performed by Kobayashi et al. (2016). The inverted final slip distribution has an area whose slip amount is large just above the hypocenter, reaching 1.3 m. We divided the fault plane into two areas; one is the area with a large slip amount (hereafter referred to as asperity), and the other is the surrounding one with a small slip amount. We fixed values of residual stress, peak stress, and Dc in both areas. We attempted to obtain initial stress values so as to minimize the residual between the simulated and inverted final slip distributions by a try-and-error method. As a result, we obtained 10 MPa as the optimal value of initial stress at the asperity. Next, we attempted to estimate spatial distribution of Dc values. For this purpose, we assumed the value to be 0.25 m in the surrounding area, and divided the asperity into four areas in the depth direction (the deepest one included the rupture initiation point (hypocenter)). We estimated Dc values, by using the same method to estimate initial stress values. As a result, we found that the Dc values became larger toward the direction of the ground surface. Comparing the inverted slip distribution with obtained heterogeneous distributions of initial stress and Dc, we found that initial stress values at the asperity were larger than those of the surrounding area, and Dc value was the smallest in the area including the rupture initiation point than the other upper three areas.

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Dynamic rupture model of the 2014 northern Nagano, central Japan, earthquake

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The 2014 northern Nagano, central Japan, earthquake occurred on the northern part of the Kamishiro fault (KF) and the northern extension of KF. The hypocenter is located at the northern end of the KF, and the rupture propagated bilaterally. Surface ruptures intermittently observed along the northern part of KF in the south of the hypocenter (Katsube et al., 2016). Waveform inversion, on the other hand, revealed that large slip mainly distributed in the north of the hypocenter (e.g. Asano et al., 2015). On the northern part of the KF, two M5-class earthquakes recently occurred, thus the slip of the 2014 northern Nagano earthquake could be suppressed. In this study, we construct a dynamic rupture model of the earthquake to understand a mechanism of the earthquake and the present stress condition on the fault.
Our fault model contains two parallel dipping segments and a vertical segment between the two segments, based on the aftershock locations (Imanishi and Uchide, 2015), the analysis of the InSAR data (Yarai, 2015), and the difference between the focal mechanism and the CMT solution. The tectonic stress proportional to depth is modeled, considering the stress inversion result (MEXT et al., 2004). We calculate dynamic rupture processes, assuming a slip-weakening friction law.
When the two dipping segments are under the same stress condition, a rupture initiating on the vertical segment propagates on the two segments simultaneously, and surface slip along the southern segment is larger than the observed one. When the stress drop on the southern segment is less than that on the northern segment, on the other hand, the maximum surface slip along the southern segment is consistent with the observation. The rupture propagates to the southern segment several seconds late, which agrees with the results of waveform inversion. Our simulation results imply that the stress accumulation on the southern segment can be insufficient to rupture because of the past earthquake.

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A Possible Dynamic Rupture Scenario of the Nankai-trough Earthquakes, southwest Japan

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We investigated possible dynamic rupture scenarios of anticipated megathrust earthquakes along the Nankai-trough, southwest Japan, taking into account the stress accumulation due to tectonic loading driven by relative plate motion. For the plate interface geometry, we used a realistic 3D non-planar plate interface geometry in and around Japan constructed by Hashimoto et al. (2004, Pageoph). The quasi-static stress accumulation was simulated according to Hashimoto et al. (2014, Pageoph), assuming an elastic surface layer overlying Maxwell-type viscoelastic half-space. We used the slip- and time-dependent constitutive law (Aochi & Matsu'ura, 2002, Pageoph) for the plate interface frictional property. Using the shear stress distribution for 150 years after the Nankai-Tonankai-like earthquake (Hashimoto et al., 2017, JpGU-AGU Joint Meeting 2017), we computed the dynamic rupture propagation by the boundary integral equation method with triangular elements (Hok & Fukuyama, 2011, GJI). A hypocenter location is one of the most uncertain parameters in the simulation. Therefore we examined various hypocenter locations and nucleation sizes to test whether or not a rupture can propagate. Under a given distribution of slip deficit and constitutive parameters, the rupture was not initiated in the Tonankai area, in the eastern Nankai area, nor in the western Nankai area at depth. In contrast, the rupture was initiated in the shallow part of the western Nankai area and propagated toward the deep portion of the western Nankai area and toward the eastern Nankai area along the edge of the asperity. The rupture then broke the Tonankai asperity and the slip evolved in the shallow portions of the eastern Nankai area. Such possible dynamic rupture scenario could not be achieved by traditional experience-based kinematic modeling approaches; thus the procedure shown in this study is quite important to constructing a physics-based earthquake generation model.

*S14-1-01
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S14. Upper mantle and transition zone dynamics and structure

Observations of Upper Mantle Discontinuity Structure

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There exist a number of seismic discontinuities throughout Earth's mantle that arise from a wide variety of mechanisms ranging from changes in mineral structure, anisotropy, the introduction of new mineral phases, the presence or production of melts, to more subtle changes in mantle composition. Of the upper-mantle boundaries, the 410 km (410) and 660 km (660) discontinuities resulting from phase changes in the mineral olivine are the most prominent, and globally define the upper mantle transition zone. The topography, sharpness, and impedance contrasts present 410 and 660 are of great value owing to their potential for revealing lateral variations in mantle temperature and composition as well as mantle dynamics. Imaging of body waves scattered from the boundaries are providing new insights on the heterogeneity present on the 410 and 660 throughout the mantle.

In addition to the 410 and 660, the ever-increasing number of seismic stations deployed around the globe is enabling study of the geographical characteristics of weaker, regional seismic discontinuities. These weaker and regionalized discontinuities are proposed to arise from a variety of mechanisms, ranging from stalled or trapped melt in the upper mantle, either at the base of the lithosphere, or above the 410 km discontinuity, transitions in the anisotropy of the olivine phase, the presence of phase changes in the pyroxene and garnet of the mantle, to the formation of seismic discontinuities from the presence of the coesite to stishovite phase transition in the vicinity of subducted and/or plume entrained eclogitic materials. These new results are adding to the diversity of seismic discontinuities found in the upper mantle and significantly improving our understanding of mantle chemical and thermal heterogeneity.

*S14-1-02
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Cold, hot mantle transition zone beneath Hawaii mapped from teleseismic Ps receiver functions

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Hawaii's remote geographic setting located far away from tectonic boundaries makes it an archetypal example of hotspot volcanism. Establishing whether this hotspot represents the classic plume theory of a vertical plume ascent from the core-mantle boundary to the surface, or perhaps of a plume that may have a more complex path, has proven challenging. In order to determine the exact trajectory of the Hawaiian plume seismic anomaly in the mantle we determine P-to-S (Ps) receiver functions to illuminate the 410- and 660-km depth mantle discontinuities beneath the Hawaiian Islands. The dataset is from waveforms recorded on land and ocean-bottom seismometers, with the latter having corrections for tilt and compliance noise. Our 3-D depth-migrated maps provide improved lateral resolution of the mantle transition zone (TZ) discontinuities. The 410 discontinuity is characterised by a deepened area beneath central Hawaii surrounded by an elevated shoulder. At the 660 discontinuity, a shallow topography is located to the north and far south of the islands, and a deep topographic anomaly is located far west and east. The TZ thickness varies laterally by +/-13 km depth: thin beneath north-central Hawaii and thick farther away in a horseshoe-like feature. We test for robust, large-scale characteristics of the TZ thickness, test the effect of a plume in the background velocity model, compare the topographic maps with seismic velocities, and compare temperature anomalies with those from geodynamic numerical models. We infer that at 660-km depth a broad or possibly a double region of upwelling converges into a single plume beneath central Hawaii at 410-km depth. As the plume rises farther, uppermost mantle melting and flow results in the downwelling of cold material, down to at least 410 km surrounding the plume stem. This result in the context of others supports complex plume dynamics including a possible non-vertical plume path and adjacent cold mantle downwellings.

*S14-1-03
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S14. Upper mantle and transition zone dynamics and structure

Slow velocities and thin transition zone indicate upwelling lower mantle beneath eastern Eurasia

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When comparing shear velocity and transition zone thickness, eastern Eurasia and the central Pacific stand out with distinctive and robust signals of slow velocities and a thin transition zone. The central Pacific lies on top of a column of slow material rising off of the Pacific large low shear velocity province. Thus, it seems the region experiences upward return flow from the lower mantle. The combination of slow velocities and a thin transition zone indicate the area is warm or dry or both. However, eastern Eurasia is a convergence zone with a long history of subducting oceanic slabs. In addition, independent compressional velocity models find the same low velocity structure within the transition zone on top of faster velocities below in the lower mantle. The tectonic history of the region indicates that the Pacific slab has been rolling to the east since the beginning of Cenozoic. We suggest that the seismic signals in the transition zone are due to upwelling lower mantle material caused by the Pacific slab sweeping across the transition zone as it falls into the lower mantle.

*S14-1-04
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S14. Upper mantle and transition zone dynamics and structure

A three-dimensional electrical conductivity image of the mantle plume of the Society hotspot in French Polynesia

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Electrical conductivity is a physical property, which is independent from seismic velocity, and is sensitive to temperature, melt fraction, and volatiles (hydrogen and carbon). By combining electrical conductivity and seismic velocity, we could constrain the physical properties of the upper mantle. The previous seismic studies found a low-velocity anomaly possible corresponding to the mantle plume beneath the Society hotspot (Suetsugu et al., 2009; Isse et al., 2006). However, because of the sparse observation array, the resolution of these images is insufficient to discuss the thermal and chemical properties of the plume. Besides, a previous marine magnetotelluric (MT) data (Nolasco et al., 1998) was obtained from too narrow region in the vicinity of the Society Islands to get a three-dimensional (3-D) image of the plume. Therefore, we conducted Tomographic Investigation by seafloor ARray Experiment for the Society hotspot Project (TIARES project) to image the possible plume with reasonable resolution using both MT and seismological observations (Suetsugu et al., 2012). In this presentation, we will focus on the results from MT data, both obtained by the previous study and the TIARES project.
We recently obtained a 3-D electrical conductivity image of the upper mantle beneath the Society hotspot (Tada et al., 2016). One of the most remarkable features is the presence of a distinct high-conductivity anomaly that extends from the mantle transition zone to a depth of approximately 50 km below the sea level. The amplitude of electrical conductivity of the anomaly is one to two orders of magnitude higher than the surrounding mantle. Assuming that the bulk mantle can be represented by a mixture of olivine and melt, the anomaly is explained by the existence of melt fraction up to 2.2 vol.% regardless of assumption of temperature. Furthermore, the existence of carbonated silicate melt is confirmed because of CO_2 in the melt is well constrained to be at least 8 wt.%.

*S14-1-05
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Seismic evidence for broad attenuation anomalies in the asthenosphere beneath the Pacific ocean

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We present QsADR17, a global model of upper mantle shear wave attenuation based on a massive Rayleigh-wave dataset (372,629 fundamental and higher-mode attenuation curves measured in the period range 50–260 s). We first correct our dataset for focusing-defocusing effects and geometrical spreading, and perform a stringent selection to only keep robust observations. Then, data with close epicenters recorded at the same station are clustered, as they sample the same Earth's structure. After this pre-selection, our dataset consists in a set of about 35,000 fundamental and higher-mode attenuation curves that constrain the Rayleigh wave intrinsic attenuation in the upper mantle. The logarithms of the attenuation along the individual rays are then inverted to obtain global maps of the logarithm of the Rayleigh-wave attenuation for each mode and each period. The set of attenuation maps is finally inverted at depth to obtain a depth-dependent model of attenuation QsADR17.

QsADR17 presents strong agreement with surface tectonics in the uppermost 200 km of the mantle, with low attenuation under continents and high attenuation under oceans. Beneath oceans, the highest attenuations are found beneath the mid-oceanic ridges at 50 and 100 km depths, but also in old oceanic basins generally in the vicinity of hotspots. Although attenuation decreases with increasing crustal ages, the presence of strong attenuating anomalies in the vicinity of hotspots produces departure from a simple half-pace cooling model. In the Pacific ocean, we observe a strong attenuating anomaly in the long wavelength component of our signal in the depth range 50-150 km. We suggest that this anomaly results from the horizontal spreading of several thermal plumes within the asthenosphere. Strong velocity reductions associated with high attenuation anomalies of moderate amplitudes beneath the East Pacific Rise, the Red Sea and the eastern art of Asia may require additional mechanisms, such as partial melting.

*S14-2-01
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Mantle transition zone, stagnant slab and intraplate volcanism in Northeast Asia

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Three-dimensional P and S wave velocity structures of the mantle down to a depth of 800 km beneath NE Asia are investigated using a large number of high-quality arrival-time data of local earthquakes and teleseismic events recorded at 2388 stations of permanent and portable seismic networks deployed in NE China, Japan and South Korea. Our results do not support the existence of a gap (or a hole) in the stagnant slab under the Changbai volcano, which was proposed by a previous study of teleseismic tomography. In this work we conducted joint inversions of both local-earthquake arrival times and teleseismic relative travel-time residuals, leading to a robust tomography of the upper mantle and the mantle transition zone (MTZ) beneath NE Asia. Our joint inversion results reveal clearly the subducting Pacific slab beneath the Japan Islands and the Japan Sea, as well as the stagnant slab in the MTZ beneath the Korean Peninsula and NE China. A big mantle wedge (BMW) has formed in the upper mantle and the upper part of the MTZ above the stagnant slab. Localized low-velocity anomalies are revealed clearly in the crust and the BMW directly beneath the active Changbai and Ulleung volcanoes, indicating that the intraplate volcanism is caused by hot and wet upwelling in the BMW associated with corner flows in the BMW and deep slab dehydration as well.

*S14-2-02
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Transition-zone imaging below Japan with ScS reverberations

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The first-order structure of the mantle transition zone (MTZ) is well known below Japan. The 410 and 660 discontinuities are clearly seen on receiver functions. The 660 shows a marked depression where the Pacific Slab is thought to interact with this boundary. The more precise shape of the MTZ, however, is unknown. Possible smaller discontinuities like the 520, are hard to interpret with clarity. Moreover, receiver functions show clear interfaces below some parts of Japan, but are hard to interpret at other parts, possibly due to multiples from the slab. To obtain a consistent image below the entire Island arc we apply seismic interferometry together with reflection imaging. Large magnitude earthquakes nearby Japan generate a clear ScS phase that is observed over the complete Hi-net array, operated by the NIED. Also, ScS reverberations of the MTZ can directly be identified on the high-sensitivity accelerometers (tiltmeters). We apply seismic interferometry to a multitude of these ScS arrivals and reverberations. Doing so, the responses are retrieved as if there were shear-wave sources at all Hi-net tiltmeter stations and zero-offset (co-located source and receiver) reflection responses were measured. We further migrate the reflection responses to a reflectivity image. This results in a pseudo-3D image of the MTZ below Japan. The main features are the topography of the 410 and 660 discontinuities, but also more subtle impedance contrasts can be followed. We discuss how our image was obtained and show an interpretation of the thus-far identified structures.

*S14-2-03
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Mantle transition zone beneath a normal seafloor in the northwestern Pacific: Electrical conductivity, seismic thickness, and water content

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We conducted a joint electromagnetic (EM) and seismic experiment to reveal the mantle structure beneath a normal seafloor at 130-145 Ma in the northwestern Pacific, where the seafloor is relatively flat and the underlying mantle is expected to be normal (free from tectonic perturbations). In the experiment, we deployed state-of-the-art instruments in two arrays from 2010-2015. Here, we report the result of analyses of the EM and seismic data for investigating the mantle transition zone (MTZ) structure. The EM data analysis revealed that an electrical conductivity structure below both arrays was approximated by an average 1-D model of the north Pacific, and showed a possible downward increase in conductivity at the top of the MTZ. From the P-wave receiver function analysis, perturbations in the MTZ thickness from a global average were estimated to be +20 km and +2 km below the northern and southern arrays, respectively, from which temperature profiles in the MTZ below these two arrays were then estimated. We jointly interpreted the profiles of electrical conductivity and thus estimated temperature, with reference to the experimental values of the effects of water on the electrical conductivities of MTZ minerals (wadsleyite and ringwoodite) from mineral physics. The upper bound of the water content below the northern array was determined to be 0.4 wt.% or 0.04 wt.%, depending on different results of mineral physics, and that below the southern array was determined to be slightly smaller. The lower bound of the water content was not constrained by our data. Our results indicate that the MTZ beneath the normal seafloor in the northwestern Pacific is drier than subduction zones, and may be a water-poor region in a plum-pudding mantle model.

*S14-2-04
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Upper-Mantle Discontinuities Across Stable South American Continent

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We stacked receiver function traces from all permanent stations of the Brazilian Seismographic Network (RSBR), as well as stations from a temporary experiment (3-Basins Project) along the SW Brazilian border, to obtain cross-section images of the major upper-mantle discontinuities in the stable South American continent.
We selected events with magnitudes > M5 in the distance range 30 to 95 degrees, visually inspected all traces, confirmed the incoming P-wave azimuth, rotated into the LQT system (using the estimated azimuth and theoretical incidence angle), deconvolved to obtain the Q-component receiver functions, and stacked along profiles. Deconvolution used a high-pass filter at 0.02Hz. Before stacking, all traces were move-out corrected to a ray-parameter of 6.4 s/deg allowing for stacking traces from different events in different stations with the same piercing-point. Stacking was done by considering piercing point locations at a depth of 520 km. Interpretation and results will be presented along sections constructed to image the major tectonic provinces in South America.
Most of the study region showed both 410- and 660-km discontinuities at the expected depths. Variations observed are mostly related to the craton high-speed roots that shift up time images of the discontinuities beneath cratonic areas. This effect can be seen beneath the San Francisco craton and the Amazon craton. A newly observed feature is the influence of the cold Nazca Slab in lowering the 660-km discontinuity under the Pantanal/Chaco basin. The flat geometry of the Nazca slab beneath the Pantanal Basin makes it closer to the 660-km discontinuity, which could potentially help to interpret the formation and evolution of the Pantanal Quaternary Basin.

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Towards 3D Kirchhoff Migration of Receiver Functions at Continental Scale

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The coda of seismic body waves contains a wealth of information about heterogeneities and discontinuities inside the Earth. By using fast Receiver Function migration techniques such as classic Common Conversion point (CCP) stacking, one can easily interpret structural features down to a few hundred kilometers in the mantle. However, strong 1D assumptions limit the scope of these methods to stable regions such as cratons and stable basins. Other more accurate 2D and 2.5D methods are based on fewer assumptions, but rely on dense arrays of stations, and are computationally expensive. Following the ideas of Cheng et al. (2016), we have implemented a fully 3D prestack Kirchhof Receiver Function migration scheme where travel times are quickly computed with the use of a fast Eikonal solver. The method is tested using both 2.5D synthetics generated with a ray theory scheme (Raysum) and 3D synthetics using a spectral element method (specfem3D). Results show that dip angles and depths can be well recovered. Application of this method to field data should prove interesting, for example, in complex subduction zones that exhibit strong heterogeneities or multiple slabs.

*S14-2-06
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Phase speed measurements of multi-mode surface waves using a broad-band array: Application to USArray

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Recent deployment of dense broadband seismic networks enables us to delineate high-resolution regional 3-D upper mantle images using surface waves, although many of surface-wave dispersion analysis with seismic arrays have primarily employed the fundamental mode only. To enhance the vertical resolution of 3-D S-wave models, higher-mode information can be of great help. However, their phase speed analysis is intrinsically difficult, since the wave trains of several modes are generally overlapped each other in an observed seismogram. Modal separation is not a straightforward issue because several higher-modes share similar group speeds, but it can be possible by utilizing multi-mode surface waves propagating across a dense linear seismic array aligned along the great-circle path. In this study, we develop an efficient method for measuring the phase speeds of the fundamental- and higher-mode surface waves based on an array-based analysis in the frequency-wavenumber domain with varying group-speed time window. The method is then applied to USArray, to map the phase speed distributions of each mode and frequency.
Extensive synthetic experiments suggest that the measured phase speeds using a linear array well represent the average structural features around the centroid of stations in the linear array. Thus, the measured multi-mode phase speeds are used as a representation of the average phase speeds around the centroid location of each station group. In this way, the phase speed distributions in North America are mapped using the measured phase speeds. Preliminary phase speed maps well reflect the major structural features of the upper mantle beneath the United States, regardless a relatively small number of employed seismic events. This method of multi-mode phase speed measurements can be of use to construct regional 3-D upper mantle models with enhanced vertical resolution.

*S14-P-01
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Unusually deep Bonin earthquake of 30 May 2015: A precursory signal to slab penetration

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An M7.9 earthquake occurred on 30 May 2015 at an unusual depth of 680 km downward and away from the well-defined Wadati–Benioff (WB) zone of the southern Bonin arc. To the north (northern Bonin), the subducted slab is stagnant above the upper–lower mantle boundary at 660-km depth, where the WB zone bends forward to sub-horizontal. To the south (northern Mariana), it penetrates the boundary, where the WB zone extends near-vertically down to the boundary. Thus, the southern Bonin slab can be regarded as being in a transitional state from slab stagnation to penetration. The transition is shown to happen rapidly within the northern half of the southern Bonin slab where the heel part of the shoelace configured stagnant slab hits the significantly depressed 660-km discontinuity. The mainshock and aftershocks took place in this heel part where they are sub-vertically aligned in approximate parallel to their maximum compressional axes. Here, the dips of the compressional axes of WB zone earthquakes change rapidly across the thickness of the slab from the eastern to western side and along the strike of the slab from the northern to southern side, suggesting rapid switching of the down dip compression axis in the shoe-shaped slab. Elastic deformation associated with the WB zone seismicity is calculated by viewing it as an integral part of the slab deformation process. With this deformation, the heel part is deepened relative to the arch part and is compressed sub-vertically and stretched sub-horizontally, a tendency consistent with the idea of progressive decent of the heel part in which near-vertical compressional stress is progressively accumulated to generate isolated shocks like the 2015 event and eventually to initiate slab penetration. The horizontal part of the stagnant slab is mechanically decoupled from the near-vertically downgoing part and is left over the 660-km discontinuity.

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Structure of Crust and Upper Mantle beneath South China Sea revealed by Surface Wave Tomography

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The South China Sea (SCS), the largest marginal sea of West Pacific Ocean, is located in the area of plate triple-junction that connect the Pacific, Eurasian, and Indo-Australian plates. Knowledge of the 3D crust and upper mantle structure is essential to improve our understandings of the geodynamical regimes and tectonic evolutions in this region. Based on the updated seismic recordings recorded by broadband stations from cooperation between Institute of Geophysics, Vietnam Academy of Science and Technology (IGP-VAST) and Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and some others stations from IGP-VAST's seismic network and international networks, we calculated more accurate group velocity dispersion curves of fundamental mode Rayleigh wave with periods from 10 s to 200 s by applying the multiple filter technique for earthquakes occurred around the SCS from 2000 to 2016. We performed the tomographic maps with the lateral resolution of 5x5 degree over the study region. Our tomographic results for Rayleigh wave at periods of 15s, 20s, 30s, and 50s showed that the group velocities in the deep seas are greater than in the shallower seas and lands, it implies that the thicknesses of crust in the deep seas are relatively shallow. However, at the periods of 80s and 120s, the low velocities are present in the Philippine and Java Trench where a lot of active volcanic eruptions exist. The 3D shear wave velocity results revealed that the crustal thickness is ranging from 10 km to 25 km. The lithospheric thickness beneath SCS is about 65-80km, it is relatively shallower than surrounding areas. The prominent low velocity zones (LVZ) exist at the depths of 70km - 200km beneath the active volcanic regions, such as Hainan island, Hon tro vocano (East Vietnam Sea), Andaman sea, Sunda shelf, southern Indochina, Sulawesi, Celebes. The LVZs provide greater thermal support suggesting that these anomalies are the sources of the volcanic rocks in this study area.

*S14-P-03
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Differences in the lithosphere seismic structure along the Brazilian continental margin in the South Atlantic from travel time seismic tomography

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Results of the P-wave travel-time seismic tomography method allowed observing differences in the seismic behavior of the lithosphere along the Brazilian continental margin in the South Atlantic. High velocity anomalies have predominance in the northern portion, which extends from the Rio de Janeiro to Alagoas States (between latitudes -22.5 and -8.5), and low velocity anomalies in the southern portion, which extends from Rio de Janeiro to Rio Grande do Sul States (between latitudes -30 and -22.5). Low velocities coincide spatially with high seismicity areas, as indicated by Assumpcao (1998) and at the high velocities with low seismicity regions. The high velocity anomalies at northern portion are related to the cratonic and low-stretched lithosphere of San Francisco paleocontinent that was connected to the Congo block before the opening of the Atlantic Ocean. Low velocities can be assigned to more weakened lithosphere, where it started the South Atlantic Ocean opening process. The oldest lithosphere in the South Atlantic, indicated by the magnetic anomalies of the oceanic floor, is higher in the southern part than in the northern part, suggesting that the continents in this region were separating, while the northern region was still connected to Africa, which could explain the lithospheric stretching process.

*S14-P-04
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Slow recycling of cold slab remnants in vigorous mantle convection

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Two dimensional numerical models of mantle convection in a cylindrical shell are employed to investigate the impact of very high viscosities in mid-mantle and lower-mantle depths as proposed by Mitrovica and Forte (2004) and Steinberger and Calderwood (2006). Models are considered with and without mineral phase transitions. Our viscosity profiles are depth dependent with deep mantle viscosities increasing to values of 300 times the viscosity of the upper mantle, and then decreasing dramatically on approaching the core-mantle boundary. The decrease of viscosity near the CMB mobilizes the overall flow despite very high mid-mantle viscosities. However, cold detached slabs sinking below continental collisions become captured by the high viscosity interior and circulate for times exceeding 200 Myr. This may account for the cold patches detected by seismic tomography below India and Mongolia.

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Detecting Seismic Anisotropy in the Mantle Transition Zone with SS Precursors

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Mineral physics experiments predict that the minerals in the transition zone (wadsleyite and ringwoodite) can have up to 8–13 % anisotropy. Seismic anisotropy is produced when anisotropic minerals are aligned by mantle flow; e.g., upwelling plume or subducting slab. However, the observation of seismic anisotropy in the mantle transition zone (MTZ) is a challenging measurement due to the limited resolution of current methods. We use a body wave approach, the SS precursors, to study the anisotropy of MTZ and associated mantle dynamics. Here, we use a broadband SS data set of 45,624 records to detect azimuthal anisotropy present near the 410 and 660 km discontinuities. Due to the low amplitude of SS precursors, we employ a slowness stacking method to improve the signal to noise ratio. We partition our data into geographic bins of SS precursor bounce points that sample with enough azimuthal coverage to be further broken down into azimuthal bins. Our goal is the detection of travel time and amplitude variance of SS precursors with azimuth. We generate synthetic seismograms by perturbing PREM model in the transition zone to predict travel time and amplitude change of SS precursors with different strength of anisotropy. We identify bin locations of South America and South Pacific Ocean that have sufficient azimuthal coverage to produce stable stacks. These bins have travel time and amplitude variations of the SS precursors that show little to no dependence on azimuth. We combine all the bins above subduction zones to detect azimuthal anisotropy caused by subduction flows. The subduction zone bins have significant travel time and amplitude variations with azimuth but their uncertainties are relatively large. The azimuthal anisotropy is quantified by fitting modeling curves to data variations, which indicates that the MTZ beneath subduction zones can have 1- 4% anisotropy. We will do further correction for the topography of MTZ to reduce the uncertainty.

*S14-P-06
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Seismic attenuation of multiple ScS phases beneath South China Sea

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The South China Sea (East Vietnam Sea) is surrounded by the Indochina peninsula, Sumatra and Borneo islands which form the Sunda block (Sunda micro-plate) and Philippine Sea plate. It plays an important role in tectonic regimes of the southeastern Asia. In order to acquire more information for understanding the tectonics in the southeastern Asia, we conduct a seismic study that investigates the seismic attenuation structure by using multiple ScS phases (ScSn) beneath South China Sea (SCS) which recorded by the broadband stations from the seismic network of Institute of Geophysics, Vietnam Academy of Science and Technology (IGP-VAST), that by the cooperation between IGP-VAST and Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and some other international stations.
From approximately 100 earthquakes (Mw > 5.5, the region: 85 – 140 E and 15 – 40 N and the period: 2000–2009), we selected and used 90 seismograms with good quality of ScSn phases obtained from 15 earthquakes and 38 stations. To avoid the effect of shallow structure, selected seismograms were filtered in bandpass of 0.01 – 0.03 Hz. These 90 event-station pairs can be classified into two directions, northwest – southeast (NW-SE) and northeast – northwest (NE-SW). Therefore, by using a spectral ratio method, we derived the averaged Q values for NW–SE, NE–SW directions and averaged of these two directions, which are Q_NW-SE = 133, Q_NE-SW = 455 and Q_Aver = 191, respectively.
The estimated value Q_Aver beneath SCS in this study is consistent with previous results and similar with some other back arc regions such as Japan Sea and Southwest Pacific. However, the significant higher Q_NE-SW implies low temperature and confirms the finish of spreading process beneath central of SCS. On the other hand, the low Q_NW-SE might be affected by active subduction Celebes Sea and it implies the low Q of upper mantle part beneath this region.

*S14-P-07
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Lithospheric Shear-wave Structure beneath North America

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The Lithosphere Asthenosphere Boundary (LAB), where a layer of low viscosity asthenosphere decouples with the upper plate motion, plays an essential role in plate tectonics. Most dynamic modeling assumes that the shear velocity can be used as a surrogate for viscosity which provides key information about mantle flow. Here, we derive a shear velocity model for the LAB structure beneath the Gulf of Mexico allowing a detailed comparison with that beneath the Pacific (PAC) and Atlantic (ATL). Our study takes advantage of the USArray data from the March 25th, 2013 Guatemala earthquake at a depth of 200 km. Such data is unique in that we can observe a direct upward traveling lid arrival which remains the first arrival ahead of the triplications beyond 18 degree. This extra feature in conjunction with upper-mantle triplication sampling allows good depth control of the LAB and a new upper-mantle seismic model ATM, a modification of ATL, to be developed. ATM has a prominent low velocity zone similar to the structure beneath the western Atlantic. The model contains strong radial anisotropy in the lid where VSH is about 6% faster than VSV. This anisotropic feature ends at the bottom of the lithosphere at about the depth of 175 km in contrast to the Pacific where it extends to over 300 km. Another important feature of ATM is the weaker velocity gradient from the depth of 175 to 350 km compared to Pacific models, which may be related to differences in mantle flow.

*S14-P-08
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Shear-wave velocity model of Palawan, Philippines from receiver function analysis

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Palawan Island is located southwest of the Philippine archipelago. Northern Palawan is part of the rifted continental margin of Eurasian plate while southern Palawan comprised the Palawan Ophiolite Complex. The crustal thickness and the regional velocity model beneath the two broadband seismic stations of the Philippine Seismic Network (PSN) in Palawan have been estimated using receiver function analysis.

Teleseismic waveforms data (30 degrees < x < 85 degrees) with magnitude 6.0 and above recorded by the PSN from January 2012 to September 2015 were used in the computation. Using the extended-time multitaper technique, the receiver functions (RFs) were calculated. Consequently, the transverse components of the stacked RFs from all available back-azimuths were inverted using genetic algorithms to check for the presence of any dipping interfaces. This was followed by the inversion of the radial components to have a more defined velocity model for certain back-azimuths.

Results showed that northern Palawan has thinner crust compared to southern Palawan. This can probably be attributed to the differences in their geology. There is also an observed velocity jump observed on both stations that could be the seismic basement.

*S14-P-09
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Seismic discontinuities in the upper mantle around Vietnam inferred from receiver functions

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Vietnam is tectonically located on Indochina and South China blocks that are separated by right-lateral Red River fault. Tapponnier et al. (1982) suggested that Indochina block was extruded southeastward by northward push of India to Asia. To investigate the structure of such blocks and its surroundings in the upper mantle, various seismological studies including tomography and splitting analysis have been performed around Indochina Peninsula. However, it seems that surveys on the seismic discontinuities in the upper mantle are insufficient in terms of their detection and determination of their undulation. In this study, we try to image seismic discontinuities in the upper mantle beneath Vietnam by using receiver functions.
We collected teleseismic P waveforms excited from earthquakes with magnitudes greater than 5.5 that occurred during March 2008 and Dec. 2015. The number of the used broadband stations deployed in Vietnam is 11. RFs are calculated through a spectral division of radial component over vertical component with a Gaussian low-pass filter of 0.16 Hz. The total number of the gathered RFs is 1,884 for all stations. The depth conversion of the time-domain RF is performed with IASP91 velocity model (Kennett and Engdahl, 1991). RF images are created by common conversion point (CCP) stacking technique.
Beneath Vietnam, the obtained RF images shows the 410 and 660 km discontinuities in the upper mantle (the 410 and 660). In a RF transect for northwest-southeast direction, we could image a depression of the 660 by 30 km in the northern part in Vietnam, compared with the depths in the southern part. Because the depth of the 410 is not changed, it seems that this represents a thickened mantle transition zone. Based on a study of global P-wave tomography, the Indian Plate subducts eastward and lies on the 660 under the northern Vietnam. Therefore, the depression of the 660 is presumably caused by cold material of the subducted slab.

*S15-1-01
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First principles investigation of the high-pressure behavior of the FeOOH-AlOOH-phase H (MgSiO4H2) system.

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It is believed that water is carried into the Earth's deep interior by hydrous minerals such as dense hydrous magnesium silicates (DHMSs) in the descending cold plate. A number of studies have been conducted to determine the high-pressure behaviors of DHMSs. In recent years, we discovered a new DHMS, phase H, stable at lower mantle pressure condition; and the solid solution formed by phase H and delta-AlOOH has been proposed as the most important carrier of water to the deepest part of Earth's mantle (Tsuchiya 2013, Nishi et al. 2014, Ohira et al. 2014). However, those hydrous phases are not denser than surrounding (dry) mantle minerals (Tsuchiya and Mookherjee 2015) and their gravitational stability in deeper part of the Earth is questionable. Therefore, the effect of denser elements such as Fe on the stability of DHMS is intrinsically connected to the ability of these phases to transport water into Earth's deep interior. In order to assess the effect of Fe on the phase relation of phase H and delta-AlOOH, we determined the high-pressure behavior of the end-member composition of this system, epsilon-FeOOH. We have discovered a new high-pressure phase transition in FeOOH at lower mantle conditions using both theoretical and experimental methods. Here we show the high-pressure structures and physical properties of the FeOOH-AlOOH-phase H system using first principles calculation and discuss possible geophysical implications.

*S15-1-02
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Large-scale compositional heterogeneity in the Earth's mantle

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Seismic imaging of subducted Farallon and Tethys lithosphere in the lower mantle has been taken as evidence for whole-mantle convection, and efficient mantle mixing. However, cosmochemical constraints point to a lower-mantle composition that has a lower Mg/Si compared to upper-mantle pyrolite. Moreover, geochemical signatures of magmatic rocks indicate the long-term persistence of primordial reservoirs somewhere in the mantle. In this presentation, I use numerical models to establish geodynamic mechanisms for sustaining large-scale heterogeneity in the Earth's mantle. Mantle flow is controlled by rock density and viscosity. Variations in intrinsic rock density, such as due to variations in basalt or iron content, can induce layering or partial layering in the mantle. Layering can be sustained in the presence of persistent whole mantle convection due to active "unmixing" of heterogeneity in low-viscosity domains, e.g. in the transition zone or near the core-mantle boundary [1]. On the other hand, lateral variations in intrinsic rock viscosity, such as due to variations in Mg/Si, can strongly affect the mixing timescales of the mantle. In the extreme case, intrinsically strong lateral heterogeneity may remain unmixed through the age of the Earth, and persist as large-scale domains in the mid-mantle due to focusing of deformation along weak conveyor belts [2]. That large-scale lateral heterogeneity and/or layering can persist in the presence of whole-mantle convection can explain the stagnation of some slabs, as well as the deflection of some plumes, in the mid-mantle [1,2]. These findings indeed motivate new seismic studies for rigorous testing of model predictions.

[1] Ballmer, M. D., N. C. Schmerr, T. Nakagawa, and J. Ritsema (2015), Science Advances, doi:10.1126/sciadv.1500815.
[2] Ballmer, M. D., C. Houser, J. W. Hernlund, R. Wentzcovitch, and K. Hirose (2017), Nature Geoscience, in press.

Mineralogical model of the lower mantle inferred from high-pressure sound velocity data

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Understanding of the mineralogical composition of the lower mantle provides important information on the evolution of the Earth. The mineralogical model of the lower mantle can be estimated by comparing the seismic velocities of the minerals under lower-mantle conditions with seismic observations. It is widely thought that spin transitions of iron in the mantle minerals may directly influence the seismic velocity structure of the lower mantle, and also suggested that the spin transition in Fe-bearing MgSiO3 bridgmanite (Fe-Brd), the major component of the lower mantle, could occur. However, the presence and its effect of the spin transition in Fe-Brd have been complex to characterize in previous studies. Especially, the effect of the spin transition on the elastic wave velocities has not been elucidated yet.
Here we present the results of acoustic wave velocity measurements on Fe-Brd by Brillouin spectroscopy in a diamond anvil cell for a pressure range of whole lower mantle in order to clarity the presence and its effect of the spin transition in Brd and constrain a more realistic model of the lower mantle. Then, we discuss the mantle convection model of the present Earth and the building materials of the Earth.

*S16-1-01
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Shear Wave Velocity Structure and Anisotropy atop the Core Mantle Boundary Beneath the Indian Ocean Geoid Low

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The Indian Ocean Geoid Low (IOGL) that spans a vast areal extent south of the Indian subcontinent is a spectacular feature on the Earth, whose origin is still debated. In this study, we investigate the shear velocity structure and anisotropy of the lower mantle beneath this geoid low and the adjoining geoid high region utilizing the differential travel times, amplitude residuals and shear wave splitting of high-quality S and ScS phases. Results reveal large variations in ScS travel time residuals indicating that the lowermost mantle beneath the IOGL is heterogeneous. The ScS-S differential travel times are ~3s slower than those predicted by IASP91 model, primarily due to velocity increase in lowermost mantle beneath the IOGL and ~2s higher than IASP91 beneath the geoid high region, due to velocity decrease in lowermost mantle. The largest negative residuals (~7.7s) are concentrated below the IOGL. Modeling of differential travel time residuals reveal that the maximum positive and negative residuals can be explained in terms of a reduction in shear velocity of 0.9% and an increase of 1.6% respectively in a 1000km thick layer above the Core Mantle Boundary (CMB). Also, the ScS/S amplitude residuals beneath the IOGL are positive, implying high impedance contrast at the CMB, owing to the presence of high velocity material. The observed high velocities are attributed to the presence of dehydrated high density slab graveyards atop the CMB beneath the Indian Ocean. Further, we investigate the lowermost mantle anisotropy by analyzing high-quality ScS phases corrected for source and receiver side upper mantle anisotropy. The splitting results reveal significant anisotropy (~1.01%) in D'' layer. The observed fast axis polarization azimuths in ray-coordinate system indicate a TTI style of anisotropy. Lattice Preferred Orientation deformation of palaeo-subducted slabs experiencing high shear strain is a plausible explanation for observed D'' layer anisotropy beneath the IOGL.

*S16-1-02
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ON THE NATURE OF LARGE ULTRA-LOW VELOCITY ZONES AT THE ROOT OF MAJOR HOTSPOT PLUMES

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Ultra-low-velocity-zones (ULVZs) are localized regions of extreme properties detected seismologically at the base of Earth's mantle, and have been found preferentially within or on the border of large low shear velocity provinces (LLSVPs). They may come in different shapes and forms. The nature and role of ULVZs in lower mantle dynamics is still poorly understood, in particular whether they are due to partial melting or the presence of solid state iron. Depending on assumptions made in geodynamic simulations, they may occur preferentially at the edges or in the middle of the LLSVPs.
We here discuss a particular class of very large ULVZ's (>800 km in lateral extent) that have been detected at the roots of broad plumes imaged in the lower mantle by seismic tomography, specifically Samoa (Thorne et al., 2013), Hawaii (Cottaar and Romanowicz, 2012) and most recently Iceland (Yuan and Romanowicz, 2017). In the case of Hawaii, a simple cylindrical ULVZ shape matched the observed shear diffracted (Sdiff) waveforms, but couldn't be uniquely constrained because of the limited illumination afforded by available data. The Iceland geometry is favorable for analyzing the effects of the ULVZ on Sdiff on paths that illuminate the root of the plume from different directions. Waveform modeling of data from 8 different earthquakes observed at arrays in north America and in China shows the presence of a large ULVZ, which, to a very good first approximation, has a regular, circular-shaped base. This shape suggests that this ULVZ is closely related to the dynamic upwelling at the base of the Iceland plume, and is therefore most likely due to partial melting of a denser and hotter than average core of the plume root, rather than to a solid state process. We also show that such structures are few and far apart, and may be characteristic of the dynamics of flow at the roots of the twenty-or-so broad mantle plumes imaged in the lower mantle.

*S16-1-03
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Waveform inversion for localized three-dimensional shear wave velocity structure within the lowermost mantle

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We formulate the inverse problem of waveform inversion for localized 3-D seismic structure, computing partial derivatives of waveforms with respect to the elastic moduli at arbitrary points in space for anisotropic and anelastic media. In this study we minimize computational requirements by using the Born approximation with respect to a laterally homogeneous model, but this is not an inherent limitation of our approach. We solve the inverse problem using the conjugate gradient (CG) method, using Akaike's Information Criterion (AIC) to truncate the CG expansion. We apply our method to invert for 3-D shear wave structure in the lowermost mantle beneath Central America, the western and northern Pacific using waveforms at periods from 12.5 to 200 s recorded at stations of USArray and F-net for deep and intermediate-depth events. Various tests show that our model is robust.

*S16-1-04
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Deep mantle heterogeneity and its relationship with deep mantle heat flow inferred from 3D spherical mantle convection with plate reconstruction system in 200 Myrs

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In recent progress on geodynamics modeling, a coupled plate-mantle-core system can be addressed from geodynamo model incorporating the heat flow across the core-mantle boundary (CMB) computed from numerical mantle convection simulations with plate reconstruction in 200 Myrs [Olson et al., 2013]. However, computing the heat flow across the CMB, it is strongly dependent on material properties of lowermost mantle minerals such as post-perovskite phase as well as thermo-chemical piles [Nakagawa and Tackley, 2008; Dekura et al., 2013; Ammann et al., 2014]. In previous study [Nakagawa and Tackley, 2008], simple tests on a relationship between deep mantle heat flow and thermo-chemical heterogeneity have been pointed out that such a relationship is not very simple as a heterogeneous boundary condition incorporating with geodynamo simulations, which is a linear treatment [e.g. Olson et al., 2013]. Here new scaling relationship between deep mantle heat flow and thermo-chemical heterogeneity derived from numerical mantle convection simulations with plate reconstruction data. On the thermo-chemical heterogeneity, it forms by the segregation of oceanic crust in the deep mantle plus the post-perovskite phase transition. Preliminary result suggests that no simple scaling relationship can be found between deep mantle heat flow and thermo-chemical heterogeneity, which is consistent with simple tests [Nakagawa and Tackley, 2008]. This also suggests that a linear scaling relationship between heat flow and seismic anomalies seems to be an over-simplified heterogeneous boundary condition for geodynamo modeling. This can also imply for a formation mechanism on Large-Low-Shear-Velocity-Provinces (LLSVPs), which could be either thermal plus post-perovskite phase or thermo-chemical piles plus post-perovskite phase.

*S16-1-06
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Effect of cation substitution on bridgmanite elasticity

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Single crystal elasticity of $MgSiO_3$ bridgmanite and cation-substituted ones has been investigated using inelastic x-ray scattering technique. The present results demonstrated that iron substitution in bridgmanite makes bulk modulus of bridgmanite larger and shear modulus smaller at the ambient conditions. This corresponds to anti-correlated behavior: bulk sound velocity increases while shear wave velocity decreases. Cation substitution may explain the anti-correlated seismic velocity anomaly observed in the LLSPVs.

*S17-1-01
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Seismic structure of the Earth's outermost core

* Satoshi Kaneshima
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In this talk we review seismological studies that investigate the Vp structure of the Earth's outermost core. The models obtained so far are reviewed. The types of data that can be used are presented. It is shown that differential travel times of SmKS waves are the most powerful data for this purpose. High-quality SmKS differential times are well fit by a Vp model of the Earth's outermost core, KHOMC (Kaneshima and Helffrich, 2013). The observations obtained so far provide the evidence for the presence at the top of the outer core of a layer that has a distinctively steeper Vp gradient than the bulk of the outer core. The most recent estimate of the layer thickness is nearly 400 km. The Vp anomalies relative to PREM for the depths 400 to 800 km below the CMB appear to be insignificant. The Vp structure of the deeper outer core is also discussed. Finally we compare the seismological models with geomagnetic models and mineral physics studies.

*S17-1-02
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Erosion of a thermally induced stably stratified layer by compositional convection in the Earth's outer core

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We propose to use radial distribution of power induced by thermal and compositional buoyancy (rate of kinetic energy production) as measure of occurrence of thermal and compositional convection.The power consists of the terms proportional to heat flux and compositional flux. The region with positive power is considered that convection is active there because kinetic energy can be produced by buoyancy force. On the other hand, in the region with negative power convection is suppressed and stably stratified layer may be produced.

We constructed a 1-dimensional thermal and compositional balance model of the Earth's core with the updated values of thermal conductivity under conditions of planetary cores derived by recent high-pressure experiments and first principle calculations, and obtained radial distributions of power for various values of the core-mantle boundary (CMB) heat flux Q. When $Q > 9.3$ TW, it is suggested that convection occurs in the whole outer core, however, a stable layer with O(100km) thickness could be produced below CMB when $Q < 4.8$ TW. Our result is in contrast with the previous studies on the assumption that the region with negative heat flux is stably stratified, where a stable layer whose thickness of O(1000km) could be produced when the heat flux across CMB is small.

*S17-1-03
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Neutrino oscillations and electron density distribution of the Earth's core

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Neutrinos, a kind of elementary particle, and consist of three species, electron neutrino, muon neutrino, and tau neutrino. They have unique property. A neutrino can change its specie to another kind of species as it pass thorough space. This phenomena called as neutrino oscillation. The probability of oscillation depends on the electron density of the media which is passed through neutrinos, so neutrino oscillation can be used as a probe to measure the electron density of the media.

Neutrinos are naturally produced in the atmosphere (atmospheric neutrino), the Sun (solar neutrino), and so on. The arrival direction distribution of the atmospheric neutrino is isotropic, so 1D electron density distribution can be measured by a single detector. The arrival direction distribution of the solar neutrino is point source, but we know the relative geometry of the Sun, the Earth, and the detector. And the Earth is rotating and revolving, so we can also measure 1D electron density distribution along solar trajectory, like CT scan. If we have several neutrino detectors which have enough sensitivity, 3D electron density distribution of the Earth also can be measured.

The matter density distribution of the Earth is already measured by using seismic data. The ratio of the matter density to the electron density is equal to the ratio of atomic weight to atomic number, i.e. the average chemical composition. By combining the matter density distribution and the electron density distribution, we can measure the average chemical composition distribution of the Earth.

We demonstrate the capability to apply the neutrino oscillation to geo-physics.

*S17-P-01
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Seismological evidence for heterogeneous lowermost outer core (F-layer) of the Earth

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The asymmetric release of light-elements at the inner core boundary (ICB) may cause a regional variation of chemical components in the outer core, especially in the layer directly above the inner core (F-layer). To verify the variation, it is necessary to analyze detailed seismic structure in the layer of two or more laterally distinct regions. However, conventional observations are insufficient to resolve the detailed F-layer structure. We developed a new method to analyze dispersion in PKPbc and PKiKP-PKPbc travel times (dT), and investigated the velocity profile beneath the northeast Pacific (Ohtaki & Kaneshima, 2015). These two observations are particularly sensitive to F-layer and relatively insensitive to the mantle and inner core.
In this study, we analyze seismograms of South Sandwich events observed in Japan using the same method. The rays turn beneath Australia. The dispersion is sensitive to the velocity gradient just above the ICB but insensitive to velocity values in the F-layer. The dispersion observations require nearly constant velocity above the ICB, which is relatively close to AK135. The dT is sensitive to the velocity values between the PKPbc turning depth and the ICB but insensitive to the velocity gradient. The dT observations are close to those predicted by PREM. The velocity model that satisfies both the observations has nearly constant and smaller velocities than PREM on the ICB, and faster ones above.
Both the observations require disparate F-layer structures in between these two regions. Velocity in the liquid core has a little dependence on temperature (Ichikawa+, 2014). Thus the difference in velocities between the two regions is ascribed to the relative abundance of light elements. The reduced velocity gradient on the ICB beneath Australia signifies chemically unmixed materials there. The higher velocities than PREM and our NE Pacific model (FVW) indicate a localized higher abundance of light elements in the F-layer.

*S17-P-02
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Outer core stratification by crystallization of SiO2

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Wavespeeds lower than PREM's near-uniform self-compression profile in the outermost outer core constitute evidence for a radial compositional gradient there, and possibly for stable stratification. Melting experiments in the Fe-Si-O system in the diamond anvil cell at outer core pressures and temperatures show crystallization of SiO2 from a variety of starting compositions. We developed a thermodynamic model of SiO2 saturation in liquid Fe at high pressure and temperature conditions suitable for modelling magma ocean and outer core processes. Significant incorporation of Si+O in the metal occurs in magma ocean conditions, 30-50 GPa, which, after the core evolves to its present temperature (3500-4500 K at the CMB), leads to exsolution of SiO2. Driving a dynamo by crystallization is quite efficient and allows one of today's strength to be powered throughout Earth history. We show that the continuous crystallization of SiO2 at the top of the core produces denser, iron-enriched liquid that mixes downward into the core. This leads to reduced wavespeeds in the top of the outer core from the net effects of the density and mean atomic weight change. Only a small change in concentration of the SiO2 component in the bulk liquid is required about 0.15 wt%.

*S18-1-01
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Geodynamical modeling and seismic observations: a step towards mapping regional structures of Earth's inner core

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The inner core displays a hemispherical difference in seismic velocity, attenuation, and anisotropy, which is well-established from seismic studies. Recent observations reveal increasingly complex and regional features. However, geodynamical models generally only attempt to explain the basic east-west asymmetry. Regional seismic features, such as depth-dependence anisotropy or variation in hemisphere boundaries, are difficult to reproduce and relatively poorly constrained by seismic data.

There are two major theories to explain the inner core hemispheres. The first invokes lateral translation of the inner core to generate a hemispherical difference in age of inner core material. The second requires a asymmetry between the hemispheres in growth rate of the inner core boundary, whereby the east hemisphere grows faster. Processes to generate the more complicated structures, such as anisotropy, sharp hemisphere boundaries, and regional features, are debated.

Seismic data sampling of the inner core is especially limited in some regions, leading to difficulty interpreting the small-scale features. Here, we present a new trans dimensional tomographic inversion for inner core seismic velocity, that accounts for the influence of uneven data coverage. The model provides improved constraints on regional-scale structure within the hemispheres, as well as lateral variation of the hemisphere boundaries, and estimates of the uncertainty in isotropic and anisotropic velocity. We compare these observations to results from our new, open-source Python code “GrowYourIC". The code simulates growth, translation, and super-rotation of the inner core, with a goal of reproducing the inner core seismic properties, as well as revealing the limitations of inhomogeneous sampling in real datasets.

*S18-1-02
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Complex inner core of the Earth constrained by differential travel times and differential ray parameters

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Various studies over the last decades have revealed complex velocity structures of the Earth's inner core., Recently, using high-quality PKPbc-PKPdf differential travel times recorded by the dense Hi-net array, we reported that compressional velocity field (Vp) in the uppermost inner core (top 350 km of the inner core) is regionally perturbed by about 1% within each quasi-hemisphere. Although we showed the existence of heterogeneity on regional scale, the precise location and size of heterogeneities could not be constrained using exclusively the perturbed differential travel times. To overcome this limitation, here we utilize the PKPbc-PKPdf differential ray parameters in addition to the corresponding differential travel times to study the Vp structure of the uppermost inner core. We find that the differential ray parameters measured by phase-weighted stacking of waveforms recorded by the Hi-net array also display regional variations in both quasi-hemispheres. This observation supports previous results and provides additional constraint on complex Vp structure. We examine a number of 2-D models with different nature of heterogeneities including the inner core boundary topography and a mushy zone to predict the observed regional variation of the differential travel times and differential ray parameters. Our estimates of the heterogeneity spectrum represent invaluable new constraints on inner core structure.

*S18-1-03
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Temporal change of seismic data associated with the Earth's inner core: inner core super-rotation or temporal change of inner core surface?

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Seismic evidence has shown that seismic compressional waves that are refracted (PKIKP) and reflected (PKiKP) off the inner core exhibit temporal changes. Two explanations have been put forward to account for the observed temporal change of the seismic data: inner core super-rotation and temporal change of inner core surface. In this presentation, we present observations of temporal change of seismic data based on global earthquake doublets found in the last 20 years and discuss the plausibility of their interpretations in the context of inner core super-rotation and temporal change of inner core surface. We show that inner core super-rotation is not required by the seismic data, cannot consistently explain the seismic data sampling different regions of the inner core and fail to track the presumed seismic scatterers appeared between some time intervals of the doublets, while temporal change of inner core surface can explain all the seismic data without requirement of inner core differential rotation. Accordingly, we present a global map of temporal change of inner core surface in the last 20 years, and discuss its implications to thermocompositional conditions near the inner core surface and driven forces of geodynamo.

*S18-1-04
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Comparison of frequency dependent reflection coefficients at the inner core boundary beneath the central America and western Pacific

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Reflection coefficients (RC) at the inner core boundary (ICB) inferred from PKiKP/PcP amplitude ratios have been used for the inferrence of the status at the inner core surface. Recently, Tanaka and Tkalcic (2015) examined the RC's freqeuncy variations and suggested a topographic variation at the ICB beneath western Pacific. It was suggested that the frequency characteristics of the RC at the ICB can be qualitatively explained by the ICB topography with height and wavelength of about 1 km. Here we additionally examine the RCs at the ICB benath the central America observed by USArray, a dense seismic network in the USA. Although the frequency characteristics of the RCs at the ICB beneath the western Pacific is complex, the RCs tend to be large at frequencies larger than 2 Hz and small at frequencues less than 2 Hz. To the contrary, some of the RCs beneath the central America are large at frequencies less than 2 Hz and small at frequencies greater than 2 Hz.
This difference suggests the existence of a large-scale regional variation at the inner core surface conditions. This variation is more significant than what we anticipated based only on the results focusing on the region beneath the western Pacific.

*S18-1-05
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Complex Iron Lattice Preferred Orientation Pattern at the Earth's Inner

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An entangled Lattice Preferred Orientation (LPO) pattern has been found at the Earth's inner core for different types of iron polymorphs. The amount of crystal alienation and its particular spatial distribution at ICB was achieved by merging the information from high-quality inner core probing seismic data [PKP(bc-df)] together with state-of-the-art ab initio calculations. Results are showing that the obtained LPO arrangement at ICB can be used as a key boundary condition for novel dynamo simulations, providing a further way to distinguish in between different geodynamical scenarios.

*S18-1-06
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Studies of inner core anisotropy from noise interferometry

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Studies of the inner core have relied on body waves (mainly PKP) and core-sensitive normal modes generated by strong earthquakes. Despite the complex pattern of the inner core anisotropy, it's shown to be predominantly cylindrically symmetric with the symmetry (fast) axis parallel to the Earth's spin axis from earthquake data. However, we recently found that the fast axis in the inner part of the inner core (IIC) is close to the equator from inner-core waves (PKIKP2 and PKIIKP2 phases) extracted from autocorrelations of earthquake coda (Wang et al., 2015). To confirm the equatorial IIC anisotropy, we examined stations at low latitudes (within ±35º), which reduces the influence of the polar anisotropy and possible contamination from the large Fresnel zones. Using a number of improved procedures of both autocorrelation and cross-correlation, we extracted high-quality empirical Green's functions at 52 globally distributed arrays. We observed large variations (up to nearly 11 s) between the PKIKP2 and PKIIKP2 phases and the pattern matches very well previous IIC model, providing further support for the equatorial anisotropy model of the IIC. Separately, earthquake-generated PKP differential travel times have been instrumental in mapping the inner core anisotropy. We found that triplicated PKP phases can be extracted from the stacks of station–station correlations (Xia et al., 2016). Both ambient noise and earthquake coda contribute to the PKP phases. However, the contributions vary with frequency and with body-wave phases. At shorter periods (5–20 s), three branches of PKP (df, bc and ab) can be extracted from ambient noise and the ab phase from earthquake coda. At longer periods (15–50 s), earthquake coda are effective in generating the df branch, but not the ab branch. The usefullness of the new type of data remains to be explored, but it's likely to complement the limited distribution of earthquake data with certain critical samplings.

*S18-P-01
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GrowYourIC: a step towards reconciling geodynamical models to seismic observations of the inner core

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The inner core structure has been well-established from seismic studies, showing heterogeneities at various scales, both radially or laterally. Yet, no geodynamical model has been successful at explaining all the features observed. One of the main limit for that is the lack of tools to compare successfully seismic observations and numerical models.

Here, we present a new Python code to compare models of the inner core structure. The code calculates properties of geodynamical models of the inner core along inner core ray paths, for random or user-specified datasets. It allows easy comparisons between geodynamical models and seismic observation, and provides various representations of models and datasets. As proof of concept, we test models which simulate fast lateral translation, and differential growth, and compare to an example inner core dataset provided with the code that samples the outermost part of the outer core, up to 107km depth. We show that a random dataset with perfect coverage produces the same average results as a real inner core dataset. However, we also find that neither simplistic geodynamical model is able to recreate the inner core seismic observations.

We discuss here the possible applications of this code for various geodynamical models. Comparing the geodynamical models and seismic observations is difficult due to the lack of seismic properties of material in the models. We will discuss how orientations of crystals can be added in this code, to compute as well anisotropy in the inner core models.

*S18-P-02
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S18. Inner core structure

Full parameter space search for a layered, anisotropic inner core using the Neighbourhood Algorithm.

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The inner core of the Earth has long been modelled seismically by simple cylindrical anisotropy with the fast axis parallel to the Earth's rotation axis. This has been quantified with the use of the inner core phase PKIKP, utilising both differential and absolute travel times. This simplistic model is popular as, to some extent, it can explain both PKIKP travel time data and anomalous splitting of normal modes. However, recently it has become apparent that such a simple model fails to fit all observed travel time data. Travel time residuals from PKPbc-PKIKP differential times, plotted against the angle with the Earth's rotation axis, form a distinctive "L" shape where polar paths, typically from the South Sandwich Islands, have a residual range of ~0-5 seconds. A simple model of cylindrical anisotropy fails to fit such extreme range of values. Whilst many models with increasing inner core complexity (e.g. the inner most inner core) have been created on an ad hoc or systematic basis, a full parameter space search has not been comprehensively carried out for travel time data. We employ the derivative free search algorithm, the Neighbourhood Algorithm, to explore multidimensional parameter space for the case of an anisotropic, layered inner core. Using a combination of absolute PKIKP travel time data from the ISC catalogue, global high-quality PKPbc-PKIKP differential travel time data hand-picked by cross-correlation, and a high volume of high-quality hand-picked differential travel time data from the South Sandwich Islands earthquakes, we search for the optimal number of layers within the inner core and the associated parameters of the cylindrical anisotropy equation. Results from this process are presented, the outcomes of which have implications for geodynamic and mineral physics interpretations.

*S18-P-03
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S18. Inner core structure

Toward probing the deep Earth's interior using spiral-arm arrays and principles of seismic interferometry

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The observations of different PKP branches on single seismograms have so far provided the primary dataset for studies of the Earth's deep interior. This dataset sheds light on many aspects of the structures and dynamics of the lowermost mantle and the inner core, such as topography of the core boundaries, or anisotropy of the inner core. Yet, the spatial coverage of these deep parts of the Earth is still far from perfect. For example, the sampling of the inner core by ray paths nearly parallel to the Earth's rotation axis (polar paths) is inherently limited due to the predominant concentration of major earthquakes at tectonic margins.
Here we focus on exploring the use of core-sensitive phases that are not widely detectable due to high noise level. Our initial approach is to utilize the array datasets collected across Australia, including three recently deployed spiral-arm seismic arrays: SQspa (in Southern Queensland), WAspa (in Western Australia), and PSAR (in Pilbara Craton, Western Australia) and the L-shape Warramunga Array (in Central Australia). The arrays are at the epicentral distance range of approx. 20-50 degrees to the majority of significant earthquakes from Southern Pacific subduction zones. We target the compressional waves that get reflected or refracted from the Earth's internal boundaries. We deploy numerical modeling with spectral element methods and array methods to verify the observations. We also test the feasibility of the seismic interferometry principles on the array data by generating virtual ray paths probing the inner core in different directions.

*S19-1-01
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S19. Plane
tary seismology

A Window into Giant Planet Structure using Saturn's Natural Seismograph

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Saturn's nonradial oscillations perturb the orbits of ring particles. Saturn's C ring is fortuitous in that it spans several resonances with Saturn's fundamental acoustic modes, and its moderate optical depth allows the characterization of wave features using stellar occultations. The growing set of C-ring waves with pattern frequencies and azimuthal order m measured by Cassini provide significant constraints on Saturn's internal structure, with the potential to resolve long-standing questions about the planet's distribution of helium and heavier elements, its means of internal energy transport, and its rotation state.

We construct Saturn evolutionary models and calculate their mode eigenfrequencies at the solar age, mapping the planet mode frequencies to resonant locations in the rings to compare with observed density and bending waves. A new feature of the models is the immiscibility of neutral helium in the liquid metallic hydrogen mantle, which leads to helium rain and the establishment of a deep stabilizing composition gradient. Similar to the model of Fuller (2014), this stratified region provides a deep cavity wherein modes close to Saturn's fundamental frequency can propagate as internal gravity waves, yielding modes that have an overall mixed character, as seen in pulsating red giant stars. The result is a more densely packed spectrum of modes that can excite resonances in the C ring, helping to explain several of the observed waves that a conventional homogeneous Saturn model--supporting only acoustic modes--cannot.

I'll assess the hypothesis that helium rain is the origin of Saturn's deep stable stratification, as well as the role of the possibly eroded core-mantle boundary. I'll touch on the related question of convective versus double-diffusive heat transport through the stably stratified region. Finally, I'll give an update on an ongoing campaign using Doppler imaging to search for Jovian oscillations from the 3m Shane telescope at Lick Observatory.

*S19-1-02
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S19. Plane
tary seismology

Probing the interior of Jupiter toward unveiling its formation: A new attempt with Jovian seismology

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The formation of Jupiter remains less well understood. Planet formation theories suggest that heavy element distribution in the Jupiter's deep interior, in particular, the size of the dense core, provides an important clue to understanding. The conventional method based on the measured gravitational moments, however, allows us to probe only shallow regions in the planetary interior. Also, the estimated core size is sensitive to high-pressure equation of state of hydrogen and helium, which is still highly uncertain. Obviously we need more direct constraints to the core size. As well known in the Earth science, the method that uses seismic waves is a powerful exploration method for planetary deep interior. Recently, we have launched a new project of network observation for detecting the free oscillation of Jupiter's surface, using Doppler spectro-imagers installed in the 1-2m class telescopes in Okayama Observatory and Ishigaki Observatory in Japan, Observatoire de Calren in France, and Apache Point Observatory in USA. In this presentation we first summarize the unresolved issues regarding the interior and origin of Jupiter and, then, introduce the newly launched project for probing the deep interior of Jupiter, which is called JOVIAL.

*S19-1-03
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tary seismology

Study of the Seismic Response of Dayside Non-LTE CO2 Emissions of Planets

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The dayside non-LTE emissions of CO2 molecules, at 4.3 micrometers wavelength, have been clearly imaged by the VIRTIS instrument on board Venus Express (Peralta et al., 2016). The emissions present a smoothly varying pattern as a function of solar zenith and a peak of emission power in the 125-140 km altitude depending on wavelength.
Previous observations also demonstrated sensitivity to perturbations induced by atmospheric gravity waves (Garcia et al., 2009). Due to the exponential amplification of low-frequency infrasonic waves, CO2 non-LTE emissions in the upper atmosphere are expected to vary during the pass of infrasounds excited by seismic surface waves. In this study, we present modeling results as a response of the emissions to ground-vibrations-created seismic surface waves.
Modeling work is performed in two steps. First, the infrasonic waves generated by a seismic surface wave train are propagated in the Venus atmosphere using realistic conditions including wind, attenuation, and sound velocity profiles, using outputs from a state-of-the-art Venus General Circulation Model (Gilli et al, 2017). Subsequently, density, temperature and pressure perturbations are used as input to the CO2 non-LTE emission modeling software. The variations of the emissions are predicted for various observation geometries and quake parameters. Detection limit is analyzed as a function of quake magnitude and epicentral distance to the source.
The modeling results obtained by this study directly apply to the VAMOS mission concept study currently considering the sounding of Venus internal structure by imaging seismic/infrasonic waves through variations of airglow emissions. Applications to other terrestrial planets will also be discussed. Similar systematic nadir observations on Mars may be possible soon with ACS/Exomars (Korablev et al, 2016).

Planetary Seismology Using Infrasound and Airglow Signatures on Venus

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The planetary evolution and structure of Venus remain uncertain more than half a century after the first visit by a robotic spacecraft. To understand how Venus evolved it is necessary to detect the signs of seismic activity. Due to the adverse surface conditions on Venus, with extremely high temperature and pressure, it is infeasible to place seismometers on the surface for an extended period of time. Due to dynamic coupling between the solid planet and the atmosphere, the waves generated by quakes propagate and can be detected in the atmosphere itself.

JPL in collaboration with ISAE and Caltech Campus is in a process of developing an instrument to measure seismic activity on Venus by in-situ measurements of infrasonic waves in the atmosphere. The overall objective of this research is to demonstrate the feasibility of sensitive barometers to detect infrasonic signals from seismic and explosive activity on Venus from a balloon platform. The seismic signals are known to couple about 60 times more efficiently into the atmosphere on Venus than on Earth, which might allow the detection of small regional quakes (magnitude ~3). We will report results on the first flight experiment that will focus on using the barometer instruments on a tethered helium-filled balloon. The results of the experiments are intended to validate the two-barometer signal processing approach using a well-characterized point signal source.

In addition, we will present another mission concept VAMOS (Venus Airglow Measurement and Orbiter for Seismicity) measuring atmospheric perturbations from an orbiting platform that could provide a breakthrough in detecting seismicity on Venus and in monitoring of seismic surface wave propagation. In contrary to the in-situ balloon strategy, VAMOS will be based on remote airglow monitoring from orbit and might allow to track the propagation of the surface waves and to determine group velocities providing key constrains on crustal and upper mantle structures.

*S19-1-05
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S19. Planetary seismology

Seismic Exploration of Europa and Other Ocean Worlds

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Seismic investigations offer a view into the deep interiors of planetary bodies and thus into the processes governing their habitability. The InSight mission and concepts for a Europa Lander and a Lunar Geophysical Network present unique opportunities for seismology to play a critical role in constraining interior structure and thermal state. In oceanic icy worlds, measuring the radial depths of compositional interfaces using seismology in a broad frequency range can sharpen inferences of interior structures deduced from gravity and magnetometry studies, such as those planned for NASA's proposed Europa Mission and ESA's JUICE mission. Seismology may also provide information about fluid motions within or beneath ice, which complements magnetic studies; and can record the dynamics of ice layers, which would reveal mechanisms and spatiotemporal occurrence of crack formation and propagation. Investigating these structures and processes in the future calls for detailed modeling of seismic sources and signatures, in order to develop the most suitable instrumentation.

We will present results of simulations of plausible seismic sources and wave-field propagation in Europa, with extension to other oceanic icy worlds, building on prior studies. We will also consider additional sources: gravitationally forced librations, which create volume-filling turbulent flow, a possible seismic source similar to that seen from turbulent flow in terrestrial rivers; downflow of dense brines from chaos regions on Europa into its underlying ocean, which possibly resemble riverine flows and flows through glacial channels and ocean acoustic signals that couple with the overlying ice to produce seismic waves, by analogy with Earth's ocean-generated seismic hum.

*S19-1-06
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S19. Plane
tary seismology

Investigating the Interior of Icy Worlds with Short Aperture Seismic Arrays

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The interiors of the icy outer satellites are currently of great interest as they may support the largest volume of habitable space within the Solar System. A key parameter of this habitability is the presence of liquid water oceans or seas beneath the frozen surface, thus geophysical investigations of the interior are crucial for understanding the structure, dynamics, and evolution of these liquid water reservoirs. Seismology will be the preeminent tool for determining the thickness of ice shells, the depth of oceans, underlying silicate bodies, and assessing Icy Worlds for habitability. Our present understanding of the seismic signals produced by Icy Worlds is limited, with the level of seismic activity at the surfaces (and interiors) likely driven by tidal processes. The harsh operating environments will limit mission observation times, making it is essential that the seismic information returned from a surface mission be of high fidelity in resolving key questions about the internal environment of an Icy World.

Such measurements can be provided by a short aperture seismic array. We define a short aperture array as a deployment of multiple 3-component seismometers, with a separation between instruments of 1-10 meters. The instruments in the array must have a sampling rate and frequency range sensitivity capable of distinguishing between waves arriving at each station. We will present 3-D synthetic modeling and analog field results that demonstrate sensing requirements and the primary advantages of such a seismic array over a single station, including the improved ability to resolve the location of the source through detection of backazimuth and differential timing between stations, ambient noise techniques, as well as the ability to improve the signal to noise ratio by additive methods such as stacking and velocity-slowness analysis. Our results inform future missions to the surfaces of Europa, Enceladus, Titan, and other objects in the outer Solar System.

*S19-2-01
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S19. Plane
tary seismology

Seismic velocity and crustal thickness inversions: Moon and Mars

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We present results from new inversions of seismic data arrival times acquired by the Apollo active and passive experiments. McMC inversions are used to constrain (i) 1-D lunar crustal and upper mantle velocity models and (ii) 3-D lateral crustal thickness models under the Apollo stations and the impact sites. A full 3-D model of the lunar crustal thickness is then obtained using the GRAIL gravimetric data. To avoid the use of any seismic reference model, a Bayesian inversion technique is implemented. We obtain robust probability density functions of interior structure parameters governed by uncertainties on the seismic data arrival times. The parameters of the inversion include the seismic velocities of P and S waves as a function of depth, the crustal thickness under each Apollo station and impact epicentre. The forward problem consists in a ray tracing method enabling both the relocation of the natural impact epicenters, and the computation of time corrections associated to the surface topography and the crustal thickness variations under the stations and impact sites. The results show geology-related differences between the different sites, which are due to contrasts in megaregolith thickness and to shallow subsurface composition and structure. However, we use the more precise LROC-located epicentral locations for the lunar modules and Saturn-IV upper stage artificial impacts, reducing some of the uncertainties observed in past studies. In the framework of the NASA InSight/SEIS mission to Mars, the method developed in this study will be used to constrain the Martian crustal thickness as soon as the first data will be available. For Insight, impacts will be located by MRO data differential analysis, which provide a known location enabling the direct inversion of all differential travel times with respect to P arrival time. Due to the high flexibility of the algorithm, the interior model will be refined each time a new event will be detected.

*S19-2-02
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tary seismology

Effects of lateral variations of Moon crustal thickness on lunar seismic wave propagation: numerical study and comparing with the Apollo seismic data

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Most recent results derived from an analysis of lunar gravity data reveal drastic lateral variations of crustal thickness around craters on the Moon. Compared with the crustal thickness of the earth, the lunar crustal thickness has strong lateral variations, which can vary from as thin as almost zero kilometer to as thick as more than 60 kilometers. However, effects of drastic variations of crustal thickness on lunar seismic wave propagation are still not well understood.
In this study we investigate how the lateral variations of crustal thickness affect the propagation of lunar seismic waves by numerical simulations and comparing with the Apollo seismic data. We apply a 2-D staggered grid pseudospectral and finite difference hybrid method to perform numerical simulations of lunar seismic wave propagation in a laterally heterogeneous crustal Moon model. The relief of lunar crust and mantle interface is defined with different height, width and position. The effects of these factors on lunar records are discussed and revealed, respectively. We then apply our method to several 2D crustal profiles derived from the most recently published global lunar crustal model to model lunar seismic wave propagation generated from both shallow and deep moonquakes, respective. Comparing between the synthetic seismograms with the Apollo observations suggests the significant effects of drastic lateral crustal thickness variation on lunar seismic wave propagation.

*S19-2-03
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tary seismology

Scattering attenuation profile of the Moon : implications for shallow moonquakes and the structure of the megaregolith

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We report measurements of the attenuation of short period seismic waves in the Moon based on the quantitative analysis of envelope records of lunar quakes. Our dataset consists of waveforms corresponding to 62 events, including artificial and natural impacts, shallow and deep moonquakes, recorded by Apollo missions 12 to 16. To quantify attenuation and distinguish between elastic and inelastic mechanisms, we measure the time of arrival of the maximum of energy tmax and the coda quality factor Qc. We employ diffusion theory in spherical geometry to model the propagation of seismic energy in depth-dependent scattering and absorbing media. To minimize the misfit between predicted and observed tmax for deep moonquakes and impacts, we employ a genetic algorithm and explore a large number of attenuation profiles quantified by the scattering quality factor Qsc or equivalently the wave diffusivity D, and the absorption quality factor Qi. The profiles that best fit the data display very strong scattering attenuation (Qsc ⊠ 10) or equivalently very low wave diffusivity (D ≈ 2 km2/s) in the first 10 km of the Moon. These values correspond to the most heterogeneous regions on Earth, namely volcanic areas. Below this surficial layer, the diffusivity rises very slowly up to a depth of approximately 80 km where Qsc and D exhibit an abrupt increase of about one order of magnitude. Below 100 km depth, Qsc increases rapidly up to approximately 2000 at a depth of about 150 km, similar to Earth's mantle values. By contrast, Qi ≈ 2400 on the Moon, which is about one order of magnitude larger than on Earth. Our results suggest the existence of an approximately 100-km thick megaregolith, much larger than what was previously thought. Using our best attenuation model, we invert for the depth of shallow moonquakes based on the observed variation of tmax with epicentral distance. On average, they are found to originate from a depth of about 50 ± 20 km.

*S19-2-04
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tary seismology

Source Time Function and Source Parameters of Lunar Quakes and Impacts.

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In this study, we present our result from the spectral analysis and source parameters of lunar quakes and impacts. To improve the spectral analysis, we used both the Apollo long and short seismic data of Apollo. We numericaly combined the two data stream to have a continuous spectrum that covers the both frequency bands. This will enable us to have a broader frequency band than single long or short period seismometer data. We take advantage of the broader frequency band to improve the estimation of spectral features and corresponding source parameters. Here we focused on corner frequencies and DC values of the spectra, which are closely related to stress drops and seismic moments. We first discuss the difference in source time function of quakes and impacts where the former is expressed with a heaviside function and the latter is expressed with a delta prime function. We will discuss how the difference is observed in the actual Apollo seismic data and compare the difference in the seismic signal. Then we will discuss the difference in the scaling law between the corner frequencies and the DC values of spectra. We studied the difference in the scaling low between 3 types of lunar seismic events, which are deep moonquake, shallow moonquake and meteorite impact. We found that not only the scaling law for quakes and impacts differ but that of shallow and deep moonquakes also differ. We conclude with the implication of the different scaling law in comparison with terrestrial examples.

*S19-2-05
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S19. Plane tary seismology

Updated travel time analysis of Apollo artificial impacts' seismic data with the precise source locations identified by LRO

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In the previous lunar seismic analyses, the artificial impacts were often used to constrain the lunar crustal thickness. The S-IVB rocket stages were deliberately impacted on the lunar surface for seismic investigation and the impact sites were obtained from radio contacts with the booster. Recently, the precise source locations of the five S-IVB impacts were updated with Lunar Reconnaissance Orbiter(LRO) image data. The updated locations resulted in change in the reference source locations for the travel time analysis with these artificial impacts. The most significant change was in Apollo 16 S-IVB. Loss of radio contact between the booster rocket stage left large uncertainties on the location of the impact. We found that Apollo16 S-IVB impact site estimated in Apollo era was different from the precise one by about 30 km. In this study, we re-analyzed artificial impacts' seismic data using the precise source locations to determine more accurately the crustal thickness of the Moon. We will present the crustal thickness around the Apollo landing site and discuss the effect of local structure that might affect the travel time analyses. We will also discuss implications for future lunar seismic exploration for better understandings of lunar crustal structure.

*S19-2-06
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tary seismology

Technical Readiness of Japanese lunar penetrator and its application to small-class space program: APPROACH

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A hard landing probe "penetrator" has been thought to be a very useful tool for constitution of network stations on the planetary surfaces and subsurface, because it provides light-weight and cost-effective capabilities of deploying scientific instruments.
The Japanese LUNAR-A penetrator project was started in 1993 and we had been continuing the development of penetrator system and the related subsystem such as a de-orbit motor, attitude control unit and tele-communication system for remote operation. Although the LUNAR-A project was officially cancelled in 2007, we had made a completion of development in penetrator probe in 2010, with a great deal of difficulties.
In these years, the follow-on mission to utilize the penetrator technology has been considered for the Japanese space program and/or within the framework of international collaborations. As the first attempt, we propose a new mission named as APPROACH (Advanced Penetrator PRObe Applied for a Challenge of Hard-landing) using a Japanese small launcher "Epsilon rocket". The APPROACH spacecraft will consists of a spin-stabilized orbiter and the LUNAR-A like single probe or two miniaturized probes with a de-orbit motor/attitude control system, and its total weight is assumed to be less than 300 kg excluding fuel, due to the limited capability of the Epsilon rocket.
After insertion of lunar orbit, one or two penetrator modules will be separated from the spacecraft and deployed on the lunar surface with an impact velocity of 300 m/sec or less. The probe(s) will penetrate into the lunar regolith up to 2 or 3 meters, and collect seismic events and heat-flow data during one-year operation at the maximum.
In this paper, we report the technical readiness of lunar penetrator and design details of APPROACH spacecraft, and then, we describe the international collaboration on this mission (simultaneous monitoring of impact flashes by ground-based and/or space telescopes).

*S19-3-01
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S19. Plane
tary seismology

The Seismic Exploration of Mars by the InSight Mission

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The InSight mission is planned for launch in May 2018 and landing on Mars about 6 months later. The payload comprises a geophysical observatory, with a seismometer (SEIS), a heat flow experiment, a geodesy experiment, and a suite of environmental sensors measuring the magnetic field and atmospheric temperature, pressure and wind. SEIS is the primary instrument of the mission and consists of a 3-axis Very-Broad-Band (VBB) instrument and a 3-axis Short Period (SP) instrument mounted on a leveling system, protected by a wind/thermal shield, and connected to the instrument electronics by a tether. The VBBs are enclosed in an Evacuated Container (EC). A leak detected in the EC late in 2015 forced postponement of the launch from 2016 to 2018, and the EC has been redesigned to prevent a recurrence.
Despite efforts with the Viking seismometers in 1976, SEIS is expected to provide the very first seismic records of Mars. Thus achieving our science goals is very challenging due to the almost complete lack of information on the seismic structure of Mars, as well as the levels of seismic activity and noise. In parallel to the instrument development by the SEIS technical team, SEIS science team efforts have concentrated on three challenges: single-station seismic analysis methodology; pre-launch estimation of the seismic and station-generated noise; and amplitude of seismic and gravity signals generated by both quakes and non-seismic sources (e.g., meteorite impacts, atmosphere, Phobos tide).
We present the status of the SEIS experiment as well as the expected performance of the seismic payload following its characterization during the 2016-17 Flight Model delivery campaign. We then summarize and review the most recent analyses predicting the seismic performance of the SEIS experiment in the Martian environment, and update estimates of seismic signals, noise (including environmental decorrelation) and planetary structure inversion perspectives.

*S19-3-02
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tary seismology

The InSight VBB seismometer: status and perspective for future missions

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SEIS is the primary payload of the NASA InSight mission due for launch on 5/2018. The instrument includes notably a Very Broad Band (VBB) 3 axis seismometer developed by the IPGP under CNES funding and subcontracted to EADS-SODERN for fabrication of the Flight Units.
Oblique VBB axis are inverted pendulum, with a 190 g mobile mass and natural frequency in the range of 0.4-0.5 Hz. A Displacement Capacitive Sensor detect the mobile mass movement with a resolution better than 5 pm/Hz^(1/2) at 1 Hz and drives the Feedback electronics. A ‘Balance Mechanism' allows adjusting very precisely pendulum balance position and correct leveling errors, gravity value uncertainty and instrument ageing. A ‘Thermal Compensation Mechanism' allows minimizing VBB thermal sensitivity passively with less than 10-5 m/s^2/K. Each axis power is smaller than 60mW and the performances requirement is 10^(-9) m/s^2/Hz^(1/2) between 0.01Hz and 1 Hz. Space qualification benefited from expertise from several CNES, JPL and SODERN experts.
By mid-February 2017, six VBBs had successfully completed their ProtoFlight Test program and one additional will be delivered before the end of the first 2017 trimester. These sensors will be integrated either in the FM Sphere (SEIS-SPH) or in its spare.
Performances in accordance with noise models have been demonstrated with previous prototypes and additional tests in 2017 will be made in BFO seismic observatory. The SEIS experiment will therefore provide high-quality seismic signal acquisition and associated seismic information during one Martian year, i.e. the nominal mission duration.
Future VBBs will be candidate for seismic missions requesting low noise sensors, such as those planed to the Moon in the 2020-2030 decade. Expected performances for a Moon VBBs will be at least one order of magnitude better than Apollo, and even larger improvement can be envisaged with an optical version, presently in development through IPGP-APC partnership

*S19-3-03
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tary seismology

The SP Microseismometer for the InSight Mission to Mars

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The InSight Mars 2018 mission is carrying a 0.3 ng/rtHz sensitivity silicon microseismometer. This microseismometer provides a sensitivity and dynamic range comparable to significantly more massive broadband terrestrial instruments in a robust, compact package.

The sensor is micromachined from single-crystal silicon by through-wafer deep reactive-ion etching to produce a non-magnetic suspension and proof mass. It is robust to high shock (> 1000 g) and vibration (> 30 grms). For qualification SP units have undergone the full thermal cycles of the InSight mission and has been noise tested down to 208K and up to 330K, with no degradation in the performance in both cases. The total mass for the three-axis SP delivery is 635 g while the power requirement is less than 400 mW.

The microseismometer has particular advantages for future planetary deployment. All three axes deliver full performance over a tilt range of up to 1 m/s2 which allows for operation without levelling. With no magnetic sensitivity and a temperature sensitivity below 2E-5 m/s2, there is no need for magnetic field monitoring and the additional resources for thermal isolation are also much reduced.In terms of performance the SP has fast initialisation, reaching a noise floor below 1 ng/ Hz in less than a minute from an untilted configuration. The noise floor is 0.3 ng/rtHz from 10 s to 10 Hz, with a long period noise below 10 ng/rtHz at 1000s. This allows tidal measurements as well as seismic monitoring for a number of proposed planetary missions.

*S19-3-04
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Conceptual Study of Small Active Seismic Exploration Package on Moons and Small Bodies

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Seismic exploration is a powerful tool to probe inner structure of planetary bodies. Developing a seismic observation package that is compatible with small to middle size spacecraft will open a new window to investigate deep interior of planetary bodies including asteroids and small satellites such as Phobos. We have been designing and developing a seismic observation package with 3 axes seismometers, active seismic source and anchoring system. This was originally designed for Japanese Martian Moons eXploration (MMX) Mission. We were not selected for the nominal payload but the selection process of optional instruments is still ongoing. Here we will present the basic concept of our seismic observation package and describe each subsystem. The seismic observation package consists of 3 components, a seismometer, an active seismic source, and an anchoring mechanism. The seismometer is based on a short period sensor that was designed for Japanese Lunar A mission. In addition to the previous design, we are developing a new feedback for higher sensitivity at lower frequencies. Current sensitivity of the SP seismometer decrease below 1 Hz but with new feedback, the sensitivity stays high down to 0.1 Hz. The active seismic source is designed so that we can control the generated waveform. This is a well-developed method in terrestrial seismology known as ACROSS (Accurately Controlled Routinely Operated Signal System). By controlling the waveform of the seismic source we can search for the reflected signal through cross correlation method. The anchoring mechanism will be necessary especially on low gravity condition. One of the major problems in planetary seismic observation is the coupling between the instruments and the ground. This will be an important issue especially for active seismic source. We will describe results of our conceptual study of the seismic observation package and discuss the possibilities of future space missions.

*S19-4-01
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SEIS/INSIGHT: One year prior the Seismic Discovery of Mars.

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InSight is the next NASA Discovery mission planned for launch in 5/2018 for landing end of 11/2018. The payload is a complete geophysical observatory, with a seismometer (SEIS), heat flux (HP3) and geodesy (RISE) experiments, a magnetometer (US) and the APSS suite of atmospheric sensors measuring wind (TWINS, Spain), atmospheric temperature and pressure (US). SEIS is the primary instrument of the mission with a 3-axis very-broad-band (VBB, F) and a 3-axis short period (SP, UK) instruments mounted on a Leveling system (LVL, D) protected by a Wind and Thermal Shield (WTS, US) and connected by a Tether (US). The 3 axis VBBs are enclosed in a vacuum thermal enclosure (EC). A leak detected in the EC during the final integration forced postponement of the launch from 2016 to 2018 and redesign of a new EC by JPL.
SEIS will provide the very first seismic records of Mars. Science goals implementation is very challenging due to the complete lack of information on the deep seismic interior structure of Mars, as well as seismic activity and surface seismic noise. In parallel to the hardware technical developments made by the hardware team, efforts of the SEIS science team were concentrated in three areas, associated with single-station seismic analysis methodology, pre-launch estimation of the seismic and station-generated noise and amplitude of seismic and gravity signals generated not only by quakes but also by other non-seismic sources (e.g. impacts, seismic waves generated by the atmosphere, or the Phobos tide).
We present the status of SEIS as well as the performances of the seismic payload, following its characterization in the 2017 Flight Model delivery activities. We summarize and review the most recent analysis made by the SEIS team predicting the seismic performances of the SEIS experiment in the Martian environment, including decorrelations performed by the APSS sensors, as well as estimates of seismic signals, decorrelated noise and structure inversion.

*S19-4-02
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tary seismology

Mars' core and what its seismological structure could reveal about the planet's evolution

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If the meteorite-based inferences of Mars' core composition are correct, it could show peculiar structural features compared to Earth's core. The liquidus diagram of iron at moderate pressures when enriched in sulfur is unusual for a core sulfur content of 11-17 wt%. From a fairly detailed liquidus diagram constructed from experimental studies, I identify a set of processes that could act within Mars' core: an iron "snow" from the core-mantle boundary's surface and a Fe(3-x)S(2) "ground fog" forming at the base of the core. Depending on temperature and bulk sulfur composition, these could form an inner core or could stratify the outer core by enriching it in sulfur, or both. Core stratification could be one explanation for the extinction of Mars' magnetic field early in the planet's history; its feasibility will be discussed. The crystallization processes in the core could be observable in the seismic data that the future Mars geophysical mission, InSight, is planned to provide. The core size, the presence of an inner core, and the wavespeed profile of the outer core, whose radial derivative provides a proxy for changes in composition, are key observables to seek.

*S19-4-03
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tary seismology

Preparing for InSight: a Blind Test for Detection and Location of Martian Seismicity

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The NASA mission InSight will deploy a lander equipped with geophysical and meteorological sensors on the Martian surface at Elysium Planitia, including two 3-component ultra-sensitive seismometers, a very broadband sensor and a short period sensor. InSight mission goals include (1) providing one-dimensional models of Mars' mantle and core to within ±5% uncertainty, as well as three-dimensional velocity models of the crust; and (2) measuring the activity and distribution of seismic events on Mars, including both quakes and impacts. The InSight launch is targeted for May 2018, landing in November 2018, with nominal deployment for 1 Martian year. InSight will return continuous data at 2 sps with the option of retrieving specific data extracts at 20 sps.

In an effort to seek methodological advances and test current single-station location approaches, and also to raise awareness and level of preparation within the scientific community for the data that will arrive from Mars, the InSight team have designed a blind test where we provide a 12 month period of continuous waveform data that simulates, to the best of our knowledge, data that we can expect to retrieve from InSight. Synthetic seismograms from tectonic and impact events are combined with expected seismic noise. We broadly invite all interested scientists to participate by analysing these Martian seismograms and providing a Martian seismicity catalogue. The test is planned to begin on 1 June 2017, with the release of the test dataset and all supplementary material, and will close 6 months later on 1 December 2017. This presentation will summarise the scope of the blind test - including how we set up the synthetic dataset; how the InSight teams will scan the data and identify and characterize seismicity; how we will evaluate different catalogues; and of course we explain how scientists can contribute to the test.

*S19-4-04
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tary seismology

Modeling the seismic signals generated by dust devils on Mars

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The 2018 InSight mission to Mars will deploy the Seismic Experiment for Interior Structure (SEIS) at the surface of the red planet. In addition to the signals generated by quakes and meteor impacts, the SEIS seismometers will continuously measure the excitation produced by the atmosphere. Among the signals of meteorological origin, dust devils and convective vortices are of special interest since they are localized, frequent and ubiquitous on Mars and they have a characteristic seismic signature.
We modeled the long-period (T > 10 s) signals of dust devils based on Large-Eddy Simulations of the daytime atmospheric dynamics at the InSight landing site and on the quasi-static response of the ground to pressure loading. Results show that vortices with typical pressure drops of 1-3 Pa can generate tilt effects of 5-20 nm/s^2 over the weak regolith. These are well above the detection threshold, and the influence area extends to a few hundreds of meters away from the vortex core. The catalog of episodes in the simulation is used to estimate the detection rate at a single station, which is expected to be as high as one episode per Martian day. Different subsurface models were considered and the possibility of using pressure and seismic data to determine the compliance of the Martian regolith is discussed. In an analog terrestrial field study, dust devils also produced infrasounds and higher-frequency seismic waves interpreted as shallow surface waves propagating in the subsurface. These additional signals contribute to better locate the vortex and to estimate the seismic velocities of the Martian subsurface down to a few tens of meter depth.

*S19-4-05
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Planned Products of the Mars Structure Service for the InSight Mission to Mars

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The InSight lander will deliver geophysical instruments to Mars in 2018, including collocated short-period and very broad-band seismometers installed directly on the surface (Seismic Experiment for Interior Structure, SEIS). Here we present the output and inversion results we expect from this mission. Routine operations will be split into two services, the Mars Structure Service (MSS) and Marsquake Service (MQS), which will be responsible, respectively, for defining the structure models and seismicity catalogs from the mission. The MSS will deliver a series of products before the landing, during the operations, and finally to the Planetary Data System (PDS) archive. Prior to the mission, we assembled a suite of a priori models of Mars, based on estimates of bulk composition and thermal profiles. Initial models during the mission will rely on modeling surface waves and impact-generated body waves independent of prior knowledge of structure. Later modeling will include simultaneous inversion of seismic observations for source and structural parameters. We use Bayesian inversion techniques to obtain robust probability distribution functions of interior structure parameters. Shallow structure will be characterized using the hammering of the heat flow probe mole, as well as measurements of surface wave ellipticity. Crustal scale structure will be constrained by measurements of receiver function and broadband Rayleigh wave ellipticity measurements. Core interacting body wave phases should be observable above modeled martian noise levels, allowing us to constrain deep structure. Normal modes of Mars should also be observable and can be used to estimate the globally averaged 1D structure, while combination with results from the InSight radio science mission and orbital observations will allow for constraint of deeper structure.

*S19-4-06
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tary seismology

The Marsquake Service: generating a seismicity catalogue for Mars

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The Marsquake Service (MQS) will be one of the ground segment services within the InSight mission to Mars, which will deploy a single seismic station on Elysium Planitia in November 2018. The main tasks of the MQS are identification and characterisation of seismicity, and managing the Martian seismic event catalogue. In advance of the mission, the InSight team have developed a series of single-station event location methods using i) multi-orbit surface waves, and ii) differential body and surface wave arrival times relying on (initially a priori) 1D and 3D structural models (Panning et al., 2015; Bozdag et al, 2016, Boese et al., 2017). These methods have been included in the operational MQS software framework. In coordination with the Mars Structural Service (Panning et al, 2016) who will provide the Martian Structure models catalogue, we expect to use iterative inversion techniques to revise these structural models and event locations (Khan et al., 2016; Panning et al., 2016). In this presentation, we introduce the methods and procedures that are being developed by the MQS in order to provide a seismicity catalogue using only the single seismic station on Mars.

*S19-P-01
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tary seismology

Seismic Wave Simulations on Mars : Comparisons between 1D interior models and effect of 3D structures

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As part of the Mars InSight mission, we explore the effects of 1D & 3D structural variations on seismic waveforms using various seismic wave propagation codes. Our motivation is to characterize seismic signals which we expect to receive from a single broad-band instrument onboard InSight.

Waveform modelling has been done by the team using different modelling techniques: modes summation, direct solution, AxiSEM, SPECFEM3D_GLOBE & SES3D. Modes, direct solution and AxiSEM seismograms have been benchmarked down to 2 s for spherically symmetric models whereas SPECFEM3D_GLOBE with AxiSEM down to 10 s. In all experiments numerical differences are much smaller than the lowest seismic noise expected for the mission. Similar benchmarks were also performed for travel times, group-velocity dispersion and body-wave amplitude estimations.

We also performed 3D global and regional simulations with SPECFEM3D GLOBE and SES3D. For 3D global simulations we superimposed 3D crustal thickness variations on top of 1D model of Sohl & Spohn (1997) capturing the distinct crustal dichotomy between Mars' northern and southern hemispheres, as well as topography, ellipticity, gravity, and rotation. The global simulations indicate clear enhancement in seismic wave amplitudes travelling through the region of Tharsis Montes where the thickest crust is located. 3D regional simulations based on 3D crustal models derived from surface composition, address the effects of various distinct crustal features down to 2 s confirming the strong effects of crustal variations on waveforms.

In order to compare the effect of the 1D structure on synthetics, we also compare teleseismic waveforms computed for 14 different 1D models down to 5 s using normal modes summation which enable us to compare and discuss the effects on waveforms of different crustal & mantle structure, and mantle attenuation. Similar comparisons are then made on the travel time & group velocities and body waves amplitudes.

*S19-P-02
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tary seismology

Estimation and detection of Mars' background free oscillations for InSIGHT mission.

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Seismic observation is a powerful tool to investigate its internal structure. The excitations of the seismic activities have been described and developed in many papers. One of the excitations is martian atmosphere. The martian atmosphere varies day by day and time by time. The pressure perturbations and wind can be seismic excitations like on Earth. The continuous excitations be enables to excite Mars' background free oscillations (MBFs). The MBFs have specific frequencies which are function of seismic properties of internal structure of Mars. The MBFs observation enables us to estimate 1D internal structure of Mars. The excitations are distributed everywhere in the martian atmosphere. It is difficult to observe whole martian climate. To solve the difficulty, we use General Circular Model (GCM). GCM can predict and reproduct long period global martian climate. The concept of the paper is to calculate MBFs using by GCMs and describe possibility of the martian hum detection. By the calculations we got minimum estimation of MBF amplitude. The amplitude is about nano gals and the martian hum can be observed by SEIS seismometer.

*S20-1-01
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S20. Earth and planetary space and remote sensing seismology; i.e., seismology without seismometers

Surface waves magnitude estimation from ionospheric signature of Rayleigh waves measured by Doppler sounder and OTH radar

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Surface waves emitted after large earthquakes are known to induce atmospheric infrasonic waves detectable at ionospheric heights using a variety of techniques, such as HF Doppler, GPS, and recently over-the-horizon (OTH) radar. The HF Doppler and OTH radar are particularly sensitive to the ionospheric signature of Rayleigh waves and are used here to show ionospheric perturbations consistent with the propagation of Rayleigh waves related to 28 and 10 events, with a magnitude larger than 6.2, detected by HF Doppler and OTH radar respectively. A transfert function is introduced to convert the ionospheric measurement into the correspondent ground displacement in order to compare it with classic seismometers. The ground vertical displacement, measured at the ground by seismometers, and measured at the ionospheric altitude by HF Doppler and OTH radar, is used here to compute surface wave magnitude. The presented results are under review for publication and are joined with some preliminary results of modeling of the Rayleigh wave signature in the ionosphere with the purpose of a full centroid moment tensor (CMT) estimation. The new magnitude and CMT estimation proves that ionospheric observations are useful seismological data to better cover the Earth and explore the seismology of other planets.

*S20-1-02
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S20. Earth and planetary space and remote sensing seismology; i.e., seismology without seismometers

Ionospheric volcanology: GNSS-TEC observation & modeling of the 2015 Kuchinoerabujima eruption

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Efforts in last decade prove that ionosphere, mainly observed by GNSS measuring the total electron content (TEC), is sensitive to geophysical phenomena as earthquakes, tsunamis, and, more recently, volcanic explosions.
Kuchinoerabujima is a volcanic island located in ~200 km southwest of Kyushu, Japan. The volcano erupted at 0:59 UT May 2015 (VEI 3).
We found a concentric acoustic wave following the eruption in GNSS-TEC time series. We used 1 Hz GEONET (GSI) data for this analysis. The observed wave seems include high frequency (5–10 mHz) pulse disappearing in the first ~300 km around the volcano and a monochromatic wave (~5 mHz) observable for more than ~20 min and reaching the distance of ~400 km. The traveltime indicates the wavefront is almost spherical. We interpreted those signals as a combination of, first, the direct shock wave propagating within the atmosphere/ionosphere and, second, the acoustic wave trapped in the lower atmosphere/ionosphere by the effect of the cut-off frequency change with the altitude.
Our observation are also supported by various ground observations: barometers (NIED; AIST), microphones (NIED; JMA) and broadband seismometer (NIED). We detected ~1 hPa wide frequency range (2–70 mHz) air wave in near-field and ~15 mHz perturbation reflecting or refracting once or twice at ~100 km from the volcano. The difference of frequency components derives from the instruments noise level or dispersion of the wave.
In order to validate our hypothesis we support and discuss our observations with the light of the modeling with the main goal of constrain some physical parameters of interest in volcanology.

Acknowledgement: We thank AIST for barometric records by the integrated groundwater observation well network for earthquake prediction of the Tonankai/Nankai earthquake. We also thanks IPGP, ERI and Hokkaido Univ. exchange programs to make our collaboration possible.

*S20-1-03
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S20. Earth and planetary space and remote sensing seismology; i.e., seismology without seismometers

Traveling Ionospheric Disturbance Triggered by Tsunami Observed by GPS and Geostationary Satellites of BeiDou

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An earthquake of magnitude 9.0 occurred near the east coast of Honshu (Tohoku area) generates a serve tsunami and disturbed the total electron content (TEC) within the ionosphere, which is called the tsunami-traveling ionospheric disturbances (TTIDs). Measurements of ground-based GPS receivers in Japan and Hawaii are employed to study TTIDs in the Pacific Ocean area. It is found that the TTID periods are of about 10-20 minutes. In the Japan region, the TTIDs initially lags tsunami wave by about 9.6 minutes, which is comparable to the estimated upward propagating time of acoustic gravity waves in the atmosphere, while in the Hawaii region, the TTID leads the underneath tsunami waves by about 1 hour, which might result from the oblique propagation of traveling atmospheric disturbances induced by tsunami waves. Finally, an observation network of ground-based receivers receiving signals from geostationary satellites of the BeiDou system is proposed to monitor TTIDs in the Asian area.

*S20-1-04
IASPEI Symposium / IASPEI05. Earth Structure and Geodynamics / S20. Earth and planetary space and remote sensing seismology; i.e., seismology without seismometer s

Inversion of the GPS -TEC induced by tsunami in order to estimate the sea level anomaly using a the normal mode modeling.

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Large underwater earthquakes (Mw > 7) can transmit part of their energy to the surrounding ocean through large sea-floor motions, generating tsunamis that propagate over long distances. The forcing effect of tsunami waves on the atmosphere generate internal gravity waves. When they reach the upper atmosphere THIS produce ionospheric perturbations . Theses perturbations are frequently observed in the total electron content (TEC) measured by the multi-frequency Global navigation Satellite systems (GNSS) data (e.g., GPS,GLONASS and the future GALILEO. In this paper, we performed for the first time an inversion of the sea level variation using the GPS TEC data using a least square inversion (LSQ) through a normal modes summation modeling technique. Using the tsunami of the 2012 Haida Gwaii in far field as a test case, we showed that the amplitude peak to peak of the sea level variation inverted using this method can be compared with less than 10 % error to the one measured by a dart buoy. Nevertheless, we cannot yet at this time invert the second wave arriving 20 minutes later. This second wave is indeed generaly explain by the coastal reflection which SPHERICAL normal modeling does not take into account. Our technique is then applied to two other tsunamis : the 2006 Kuril Islands tsunami in far field, and the 2011 Tohoku tsunami in closer field. This demonstrates that the inversion using a normal mode approach is able to estimate fairly well the amplitude and waveform first arrivals of the tsunami waveform.

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Modeling Earthquake-Induced Travelling Ionospheric Disturbances

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In this research, we apply the three-dimensional, time-dependent, and physics-based model WP-GITM (Wave Perturbation – Global Ionosphere-Thermosphere Model) to simulate earthquake-ionosphere coupling via acoustic-gravity waves (AGWs). WP-GITM consists of an analytical model that solves for the neutral atmospheric perturbation at 100 km altitude due to AGWs generated from a ground source, as well as a fully physics-based model that provides corresponding ionospheric and thermospheric perturbations. We utilize available seismometer data and explore AGW source representations for two major earthquakes. Our simulated ionospheric total electron content (TEC) disturbances are validated against Global Positioning System ionospheric observations. It is expected that we gain more insights into the earthquake-ionosphere coupling process using our advanced modeling capabilities and observational data.

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Exploring the Use of Airglow Measurements for Detecting Seismicity on Venus

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Investigating seismology on Venus is expected to greatly improve our knowledge of the internal structure and present-day activity of the planet: these are indeed poorly constrained by observations. However, classical seismology is currently unattainable due the extreme surface temperatures and high atmospheric pressure. Nonetheless, the thick and dense atmosphere is strongly coupled to the ground and therefore Venus is an excellent candidate for atmospheric remote-sensing seismology.

The nightside of Venus is characterized by a bright airglow layer of atomic oxygen at 90-120 km altitude and we explore the possibility of detecting fluctuations in the airglow intensity induced by quakes. On Earth, airglow response to tsunamis has been measured both with ground-based (Makela et al., 2011) and satellite (Yang et al., 2017) techniques. Here, we computed seismograms inside the airglow layer using normal-mode summation for a fully coupled atmosphere-solid planet system (Lognonne et al., 2016). The corresponding variations in the volumetric emission rate are calculated for a realistic background model (Soret et al., 2012) and vertically integrated to reproduce the signals that would be seen from orbit. The noise level of existing airglow cameras suggests that the fluctuations coupled to Rayleigh waves generated by quakes of magnitude 5 and above occurring on the nightside of the planet may be detectable up to about 60 degrees in epicentral distance. A major advantage of this technique is that a single orbiting camera may be sufficient to serve the role of a seismic network. Identification and tracking of the waves will indeed lead to source localization, magnitude estimation and measurement of Rayleigh-wave velocity. In particular, it is expected that this would significantly constrain seismicity on Venus and, through Rayleigh-wave dispersion, the structure of the crust and upper mantle.

*S20-P-01
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Atmospheric interior resonances : theory and observation on Earth and comparative analysis for terrestrial planets with atmosphere

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Resonance effects occur with the atmosphere when the dispersion curves of the Earth interior normal modes cross or are close from atmospheric dispersion curves. On Earth, this occurs for example between the Rayleigh surface waves branch and the acoustic branches and between the tsunami branch and the atmospheric gravity branches.
These resonances are not always retrieved in the atmospheric signals, as the later depend not only on the coupling with the atmosphere as a whole, but also on the location of the sensor (for in situ observation) or of the sounding zone (for remote sensing observation). We illustrate this altitude effects with both theoretical examples and observations, noting that ionospheric observation, because of their altitude, are mostly sensitive to the resonances associated no non atmospheric trapped resonances. Observations shown are either related to Rayleigh waves (with Doppler and GPS sounders) or to tsunamis (mostly with GPS-TEC). We also discuss how the strength of these resonances changes with Local Time, as well as with other changes in the atmospheric structure.
We then conclude by a comparative analysis of the resonances effects on other terrestrial planets, focusing on Venus, Mars and Titan, and discuss the expected impacts of these resonances for future atmospheric ionospheric seismic observation on these bodies. We especially discuss the impact of the coupling on Venus, which is strong enough to modify significantly the attenuation factors and group velocity of Rayleigh waves in contrary to the Earth case, where such perturbations remain small for both Rayleigh and Tsunamis.

*S20-P-02
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Recording TEC profiles from aircrafts for tsunami early warning

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Up to now, the best system to detect a tsunami in open ocean is the DART network of ocean-bottom pressure sensors. While the DART system has contributed significantly to tsunami early-warnings during recent events, the network suffers from an inadequate distribution of sensors and from serious maintenance problems. To increase the efficiency of the warning system, we developed a software to estimate the flight route of aircrafts for an optimized data acquisition of the Total Electron Content (TEC) using their onboard GPS receiver. The fundamental goal is to then invert these data to estimate the minimum tsunami height. This software has been developed in the framework of the TWIST project (Tsunami Warning and Ionosphere Seismic Tomography), funded by the Office of Naval Research of the US Navy. It estimates the most suitable take-off time(s) for the aircraft to record TEC data. After the calculation of the tsunami travel times, a flight route is estimated for a given take-off time. Knowing the location of the satellites, the locations of the Ionospheric Pierce Points are determined. Then, the simulated TEC values are assigned to these locations, using a modified version of the NeQuick electron density model (Nava et al., 2008). Finally, the quality of the data recorded during the flight route is assessed. The criterion is defined in order to favor (1) the flight routes with a maximum number of satellites in visibility by the aircraft and (2) the flight routes with a maximum of complete data during the recording time for a given satellite. This processing is made for different take-off times to choose which time interval is the most appropriate for the recording of TEC data. We are working with the CIRPAS (Center for Interdisciplinary Remotly-Piloted Aircraft Studies) in Monterey, California, to realize TEC measurements using Twin Otter aircrafts. We hope that our collaboration will make possible a first flight in the following month.

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Signals in the ionosphere generated by tsunami earthquakes: observations and modeling support

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Forecasting systems failed to predict the magnitude of the 2011 great tsunami in Japan due to the difficulty and cost of instrumenting the ocean with high-quality and dense networks. Melgar et al. (2013) show that using all of the conventional data (inland seismic, geodetic, and tsunami gauges) with the best inversion method still fails to predict the correct height of the tsunami before it breaks onto a coast near the epicenter (< 500 km). On the other hand, in the last decade, scientists have gathered convincing evidence of transient signals in the ionosphere Total Electron Content (TEC) observations that are associated to open ocean tsunami waves. Even though typical tsunami waves are only a few centimeters high, they are powerful enough to create atmospheric vibrations extending all the way to the ionosphere, 300 kilometers up in the atmosphere. Therefore, we are proposing to incorporate the ionospheric signals into tsunami early-warning systems.
We anticipate that the method could be decisive for mitigating “tsunami earthquakes" which trigger tsunamis larger than expected from their short-period magnitude. These events are challenging to characterize as they rupture the near-trench subduction interface, in a distant region less constrained by onshore data. As a couple of devastating tsunami earthquakes happens per decade, they represent a real threat for onshore populations and a challenge for tsunami early-warning systems. We will present the TEC observations of the recent Java 2006 and Mentawai 2010 tsunami earthquakes and base our analysis on the simulation code SPECFEM3D (Komatitsch & Vilotte, 1996), which solves the wave equation in coupled acoustic (ocean, atmosphere) and elastic (solid earth) domains. Rupture histories are entered as finite source models, which will allow us to evaluate the effect of a relatively slow rupture on the surrounding ocean and atmosphere.

*S21-1-01
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Imaging lithospheric seismic discontinuities beneath Cascadia using S-to-P receiver functions

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Strong, sharp seismic discontinuities in the 60 – 110 km depth range are now frequently imaged and sometimes related to the lithosphere-asthenosphere boundary. However, determining the exact relationship has proven challenging, and interpretations diverge particularly between the continents and the oceans. Here we use S-to- P receiver functions recorded by the Cascadia Ocean Bottom Array and the western most Transportable Array to image crust and upper mantle discontinuity structure beneath the Juan de Fuca and Gorda Oceanic Plates and western North America. We handpick events from epicentral distances 55 – 80 degrees away, choosing 5021 waveforms of which 343 are from ocean bottom seismometers. We use an extended time multi-taper technique to deconvolve the waveforms and migrate to depth in 3-D. We image a positive phase, or velocity increase with depth, that corresponds to an oceanic Moho at 6 – 7 km depth and a continental Moho at 33 – 37 km depth. We also image a negative discontinuity beneath the ocean plate that thickens with age from 25 – 45 km depth beneath the oceans in general agreement with expectations from half-space cooling. Waveform and geodynamic modelling indicate that these are defined by melt. This suggests that melt exists at the base of the plate, defining it, and that melt is likely transported along the base of the plate towards the mid-ocean ridge. In addition, we image a deeper discontinuity at 55 – 75 km beneath the continental lithosphere also likely related to the lithosphere-asthenosphere boundary.

*S21-1-02
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The depth of the LAB across Cenozoic Europe from seismological studies

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In this contribution we shall review the seismological experiments carried out over the last 3 decades across the Cenozoic regions of Central and Western Europe. In particular we will focus on the studies dedicated to ECRIS and the Variscan orogeny, the two most important tectonic features across these active domains.
In order to be able to draw some conclusions on the geodynamic behaviour the complementary methods of seismic tomography, receiver function and SKS-studies are used.

Since more than three decades, detailed seismic studies have been carried out across the Hercynian massives (i.e. the Armorican Massif, the Massif Central, the Vosges-Black Forest mountains, the Eifel region and the Bohemian Massif) and the adjacent graben systems of Cenozoic ages (Limagne graben, the Rhine graben and the Eger graben). These studies suggest that while the depth of the Moho and crustal structures across the grabens are only slightly thinner than the general crustal structure across central Europe, do the Upper mantle structures differ quite strongly. While the Massif Central and the Eifel region are underlain by so-called “Baby plumes", shows the Bohemian Massif a rather broad uplift of the asthenosphere and the southern Rhine graben – once thought as a “classical plume" – a rather negligible “plume" influence. The lithosphere-asthenosphere boundary seems to be rather flat at around 100km depths with a narrow but marked upwarping in some of the regions affected by tertiary volcanism, namely the Massif Central and the Eifel area, where the heat influx and the regional stress pattern seem to be the crucial element.

We shall compare the different regions in the light of the different studies and their geodynamic context.

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Imaging the lithosphere - top to bottom - of the Hikurangi plateau as it subducts beneath North Island, New Zealand

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We present the first images, from active seismic source profiling, for both top and bottom of an oceanic plateau as it undergoes subduction. Active continental margins provide a useful platform from which to conduct seismic experiments to image subducting oceanic lithosphere. This is especially so if the subduction is at a low angle (5-20 degrees), as it is beneath North Island, New Zealand. Here we report results of the SAHKE experiment that was designed to image the locked section of the Hikurangi subduction zone , just north of Wellington city. The on-land section of the SAHKE profile was ˜ 90 km long, along which 900 seismographs were distributed. 12 x 500 kg explosive charges were detonated in 50m deep bore holes. Structure for the top of the plate, at a depth of 15-30 km beneath the land surface was well imaged and features a suite of strong reflections that are interpreted to represent a ˜ 5 km-thick sequence of low–wave speed sediments/and or serpentinites. We also recorded the Moho reflection from the subducted plate. The thickness of the oceanic crust is calculated to be 10.5 ± 1.5 km, which is about 50% greater than regular oceanic crust. This is significantly less than the ˜ 35 km thickness of oceanic crust associated with the Ontong Java plateau, which the Hikurangi Plateau was once thought to be connected to.
Coherent reflections within the 8-20 Hz band were recorded at 27-32 s two-way travel time, which turn out to be from a double band of reflectors at depth of ˜ 100 km that dip ˜ 12 -15 degrees to the NW, parallel to the top of the plate. We interpret these reflections as marking a ˜ 10-km-thick channel of ponded melt that defines the base of the mechanical boundary layer for the ˜ 74 km thick plate. This is consistent with the LAB of a thin oceanic plateau, but a mid–lithospheric discontinuity from a thick, old, oceanic plate cannot be ruled out.

*S21-1-04
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Imaging the Pacific lithosphere discontinuities near 60 km depth using SS precursors and constraints on defining mechanism

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Oceanic lithosphere provides an ideal location to decipher the nature of the lithosphere – asthenosphere system which is vital to our understanding of plate tectonics. Although a thermally defined plate explains many first order observations such as bathymetry and heat flow. Observations of sharp mantle discontinuities are not well-understood. Here we use SS precursors to image the discontinuity structure across the Pacific Ocean using 24 years of teleseismic data. We image a sharp velocity discontinuity (3 – 15% drop over < 21 km) at 30 – 59 km that increases in depth with age from the ridge to at least 36 My according to conductive cooling along the 1100 degree C isotherm. The discontinuity is imaged at a depth of 35 – 80 km for seafloor > 36 My. The shallow discontinuity at about 60 km is laterally continuous across most of the Pacific. It has recently been suggested that discontinuities in this depth range may be explained by an increase in radial anisotropy with depth. We evaluate the potential for an anisotropic variation to explain the discontinuities. We test surface wave depth resolution of radial anisotropy and estimate the apparent isotropic seismic discontinuities that could be caused by a change in radial anisotropy scattered wave imaging using synthetic seismograms. We find strong surface wave azimuthal anisotropy at 0 – 50 km depth at an example case near the East Pacific Rise (EPR) implies a strong shallow radial anisotropy if caused by aligned olivine. An additional strong increase in anisotropic strength with depth from 50 – 100 km is not supported. We find that neither an increase in radial anisotropy with depth caused by aligned olivine or frozen-in compositional layering can easily explain the observations from scattered waves. Another mechanism such as melt or composition may be required. The strength and pervasiveness of the boundary suggests that it is likely related to the lithosphere – asthenosphere boundary.

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Lithospheric heat production: calculating mantle heat flow from asthenospheric shear velocity variations

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Estimates of heat production in the continental crust are derived from a combination of petrological, geochemical, and geophysical constraints, with some models predicting variability in the abundance and distribution of the heat-producing elements (HPE: U, Th, K) in the lower and middle layers (from correlation of SiO2 and VP), and constant HPE concentrations in the upper crustal layer. Geophysical models (e.g., CRUST 1.0) define layer density, thickness, and VP variation on a 1x1 degree grid. Geochemical and geophysical models are used to calculate the surface heat flow, assuming a Moho heat flux, with up to 100% difference between observed and predicted surface heat flows. Inversion of crustal heat production from surface heat flow gives non-unique solutions due to a poorly constrained Moho heat flux. We explore how mantle heat flux variations calculated from seismic constraints affect the agreement between observed surface heat flux and that predicted by models of continental crust.

Asthenosphere temperatures are derived from dVs/dT relationships, global Vs tomographic models, LAB depth models, mantle potential temperature and adiabat. LAB temperature is given as the intersection of the mantle adiabat with the LAB. Using this LAB temperature, mantle adiabat, and estimates of mantle thermal conductivity, we calculate the LAB heat flux on a 1x1 degree grid. Subtracting the predicted sub-LAB heat flux from the observed surface heat flow for Archean and Proterozoic crust gives a heat production in each lithospheric column. We then calculate the heat production in the continental crust for each column by removing heat production in the lithospheric mantle, as determined from a xenolith-derived geotherm. We evaluate the implications for crustal heat production due to various model parameters, including biases in the seismic LAB determinations, use of different tomographic models, and assumptions about mantle potential temperature and dVs/dT relationships.

Continental growth in eastern Australia: Insights from the mantle lithosphere

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The Tasmanides of eastern Australia is a complex series of Palaeozoic to early Mesozoic orogens which is juxtaposed against the eastern margin of the Precambrian shield region of central and western Australia. The subduction-accretion process was accommodated by retreat of the proto-Pacific plate along the eastern margin of Gondwana, which incorporated both Australia and Antarctica. A large region of the Tasmanides and its transition to Precambrian terrane in the west has been gradually covered by a transportable seismic array called WOMBAT, which has been in operation for the last two decades and has involved the deployment of over 750 stations.

Here, the latest body wave tomography results for the upper mantle will be presented, which reveal a number of distinctive features underlying the Palaeozoic terrane. The dominant long-wavelength signature is a gradual decrease in (P-wave) velocity from near the Proterozoic-Palaeozoic transition zone to the continental margins in the south and east. However, a pronounced N-S oriented “fragment" of high velocity mantle material, not present in lower resolution regional and global tomography models, is located some 200-300 km inboard of the east coast, which acts to form a low velocity embayment beneath the Lachlan Orogen, the southernmost fold belt of eastern mainland Australia. By using seismic wavespeed variations to infer changes in lithospheric thickness, we find that the Lachlan Orogen is likely underlain by thin lithosphere, with the high velocity “fragment" to the east forming a salient of thick lithosphere that attaches to the cratonic interior of Australia to the north. These results support the idea that the core of the Lachlan Orogen is a large orocline that formed due to differential roll-back of the proto-Pacific margin of east Gondwana, which had the effect of introducing, via continental transform faulting, older and thicker lithosphere from the north into a region dominated by accreted oceanic lithosphere.

*S21-2-02
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Tearing of Indian mantle lithosphere from high-resolution seismic images: Implications for lithosphere deformation coupling in southern Tibet

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What happens to the Indian mantle lithosphere (IML) during the Indian-Eurasian collision and what role it has played on the plateau growth are fundamental questions that remain unanswered. Here, we show clear images of the IML from high-resolution P and S tomography, which suggest that the subducted IML is torn into at least 4 pieces with different angles and northern limits, shallower and further in the west and east sides while steeper in the middle. Deep earthquakes in the lower crust and mantle are located almost exclusively in the high-velocity (and presumably strong) part of the Indian lithosphere. The tearing of the IML provides a unified mechanism for late Miocene and Quaternary rifting, current crustal deformation, and deep earthquakes in southern and central Tibetan Plateau and suggests that the deformation of the crust and the mantle lithosphere is strongly coupled.

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Mantle lithosphere edges of Baltic Shield and East European Craton retrieved by seismic anisotropy

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Several passive seismic experiments provided data for detailed studies of upper mantle anisotropy, namely fabrics of the mantle lithosphere. Lateral variations of body-wave anisotropic parameters, retrieved from teleseismic P-sphere patterns, shear-wave splitting and teleseismic tomography, detected domains of mantle lithosphere with differently oriented fossil fabrics (Babuska and Plomerova, PEPI 2006) and delimited their extent in the upper mantle. The south-western edge of the Baltic Shield, adjacent to the Sorgenfrei—Tornquist Zone that separates the Precambrian and Phanerozoic parts of Europe, is characterised by a sharp change of both the lithosphere thickness and fabrics (Plomerova et al., Tectonophysics 2001). On the contrary, in the central part of the Trans-European Suture Zone, a broad transition between the East European Craton and Phanerozoic Europe, no significant change in the mantle lithosphere fabric has been detected across the Tornquist–Teisseyre Zone (Vecsey et al., SE 2014), but westward lithosphere thinning. Results of body-wave tomography (Chyba et al., PEPI 2017) suggest thrusting the Phanerozoic European lithosphere over the East European craton. Change of the lithosphere thickness around the contact of the Proterozoic and Archean parts within the Baltic Shield is insignificant (Plomerova and Babuska, Lithos 2010) and the contact appears as a broad transition in the south-central Fennoscandia, which can be modelled as an Archean wedge penetrating into the Proterozoic mantle (Vecsey et al., Tectonophysics 2007). This model is supported by xenolith ages (Peltonen and Brugmann, Lithos 2006). Further to the north, the Archean-Proterozoic boundary follows the surface trace of the Baltic-Bothnia Megashear Zone (Plomerova et al., SE 2011). Anisotropic tomography (Munzarova et al., under prep.) indicates a westward continuation of the cratonic lithosphere that retains its own fossil fabric.

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Shear Wave Splitting and Upper Mantle Flow in Mexico

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The results of shear wave splitting studies of the upper mantle in Mexico are presented. Upon entering an anisotropic medium a shear wave becomes split, meaning that a fast and a slow wave are produced. Two parameters are used to quantify anisotropy. These are the fast polarization direction and the delay time between the fast and the slow wave. The covariance method of Silver and Chan [1991] was used. Data from both permanent and temporary networks were used. Measurements were made mostly from core-transmitted phases such as SKS, but also S waves from local intraslab events were used. A motivation for studying seismic anisotropy is to determine the nature of upper mantle flow and its relationship to tectonic processes. Mexico has many diverse tectonic environments, some of which are currently active, or were formerly active, and have left their imprint on seismic anisotropy. This has resulted in a wide variety of mechanisms for driving mantle flow. The following regions have been studied: the Middle America Trench, the Baja California peninsula, the Western Mexican Basin and Range, northern and northeastern Mexico, and the Yucatan peninsula. Depending on the unique characteristics encountered within each region, some of the various explanations proposed for the anisotropy are (1) entrained subslab mantle flow, (2) corner flow in the mantle wedge, (3) slab rollback, (4) mantle flow driven by the extinct Farallon slab, (5) vertical upwelling at a former ridge, (6) early episodes of extension, (7) mantle flow around the edge of the North American craton, and (8) absolute motion of the North American plate.

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Numerical simulation of 3D mantle flow in the Aegean (Hellenic) and Cyprus subduction systems linking to seismic anisotropy beneath the eastern Mediterranean and Anatolia

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Seismic anisotropy is a key parameter in understanding plate movements in relation to past/present deformation styles, and is usually controlled by the mantle flow patterns as a consequence of dynamic interactions between a relatively buoyant and dense subducting oceanic plate and the surrounding mantle. This study examines the evolution of splitting parameters as one of the most well established measure of seismic anisotropy and their source for the last 30Ma based on a 3D dynamic modeling performed for the eastern Mediterranean. Our model setting is chosen to be as similar to reality as possible as it consists of an active and fast moving Anatolian micro-plate, slow moving African and Arabian plates and an oceanic plate in between. The retreat of the slab in the Aegean, the alleged tear in the subducting slab close to the Cyprian trench and the break off in the slab in Eastern Anatolia are considered in our modeling study in order to see their influence on mantle flow and the splitting parameters. The synthetically calculated fast polarization directions (FPDs) mostly showed a decent matching with those inferred from previous seismological observations (SKS splitting measurements). Regions of similarities between FPDs measured from synthetic and observed shear waves mostly indicate N-S to NE-SW orientations of fast shear waves, which are parallel to the extension and in general perpendicular to the trench. Pattern of FPDs seems to be more complex near the trench. Our modeling results suggest that the development of tear in the African slab and the detachment of the Arabian plate appear to have a significant influence on the FPDs. The mantle flow through the tear close to Cyprus and the break off in the east can be identified clearly, despite their recent appearances. A circular pattern around the edges of the slab can be observed as well as disruptions of the overall general fast polarization direction due to the flow through the tear in the slab.

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Seismic anisotropy tomography of the Western Pacific subduction zones

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We present 3-D images of azimuthal anisotropy tomography of the crust and upper mantle of the western Pacific subduction zones, which are determined using a large number of high-quality P and S wave arrival-time data of local earthquakes and teleseismic events recorded by the dense seismic networks in and around the Japan Islands. A tomographic method for P-wave velocity azimuthal anisotropy is modified and extended to invert S-wave travel times for 3-D S-wave velocity azimuthal anisotropy. A joint inversion of the P and S wave data is conducted to constrain the 3-D azimuthal anisotropy of the Japan subduction zone. Main findings of this work are summarized as follows. (1) The high-velocity subducting Pacific and Philippine Sea (PHS) slabs exhibit trench-parallel fast-velocity directions (FVDs), which may reflect frozen-in lattice-preferred orientation of aligned anisotropic minerals formed at the mid-ocean ridge as well as shape-preferred orientation such as normal faults produced at the outer-rise area near the trench axis. (2) Significant trench-normal FVDs are revealed in the mantle wedge, which reflects corner flow in the mantle wedge due to the active subduction and dehydration of the oceanic plates. (3) Obvious toroidal FVDs and low-velocity anomalies exist in and around a window (hole) in the aseismic PHS slab beneath Southwest Japan, which may reflect a toroidal mantle flow pattern resulting from hot and wet mantle upwelling caused by the joint effects of deep dehydration of the Pacific slab and the convective circulation process in the mantle wedge above the Pacific slab. (4) Significant low-velocity anomalies with trench-normal FVDs exist in the mantle below the Pacific slab beneath Northeast Japan, which may reflect a subducting oceanic asthenosphere affected by hot mantle upwelling from the deeper mantle.

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Constraints on Anisotropic Velocity Structure of the Lithosphere-asthenosphere System in the Central Pacific from the NoMelt OBS Array

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Seismic anisotropy represents one of the primary mechanisms for probing deformation and melting processes in the earth. Seismic models of oceanic upper mantle are conflicting regarding the relative importance of these deformation processes: seafloor-spreading fabric is very strong just beneath the crust-mantle boundary at relatively local scales, but at global and/or ocean-basin scales, oceanic lithosphere is found to be weakly anisotropic when compared to the asthenosphere. There is little consensus on which of these factors are dominant, in part because observations of detailed lithosphere structure are limited. To address this discrepancy, we conducted the NoMelt experiment on ~70 Ma Pacific lithosphere with the aim of constraining upper-mantle circulation and the evolution of the lithosphere-asthenosphere system. The Rayleigh waves display strongest azimuthal anisotropy with within the high-velocity seismic lid, with fast direction coincident with seafloor spreading. A minimum in the magnitude of azimuthal anisotropy occurs within the middle of the seismic low-velocity zone. In no depth range does the fast direction correlate with the apparent plate motion. High-frequency Love waves suggest positive radial anisotropy (Vsh > Vsv) and azimuthal anisotropy with a strong 4-theta azimuthal signal in the upper 50 km of the mantle. To further evaluate the processes producing asthenospheric fabric, we measure teleseismic P- and S-wave multi-channel delay times to constrain lateral velocity variations beneath the array.

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Upper mantle structure beneath the Pacific Ocean revealed by land and seafloor broadband observations

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Seismic tomography studies have revealed the structures and dynamics of the Earth's interior. However, spatial resolution of the oceanic region is worse compared to the continental region caused by sparse distribution of the land seismic stations.
In last 20 years, our Japanese seafloor broadband observation groups have conducted several temporary seafloor seismic array observations using broadband ocean-bottom seismographs (BBOBSs) in the Pacific Ocean. Total number of BBOBSs we used is more than 100. U.S. groups have also conducted the seafloor seismic array observations in the Pacific Ocean, and seismograms recorded by their BBOBSs are available from IRIS data center.
These BBOBS data enable us to improve the spatial resolution of the Pacific region.
We analyze three-dimensional shear wave velocity structure in the upper mantle beneath the Pacific region using land and seafloor seismic data by surface wave tomography method.
We have used a surface wave tomography technique in which multimode phase velocities of the surface wave are measured and inverted for a 3-D shear wave velocity structure by incorporating the effects of finite frequency effect and ray bending.
Checkerboard resolution tests suggests that spatial resolution is about 1000 km in the eastern Pacific Ocean but is about 600 km in the western Pacific Ocean.
Large scale heterogeneity of the upper mantle in our obtained model is consistent with previous tomography models. Strong radial anisotropy can be seen in the central Pacific at depths of 100 - 200 km and weak anisotropy can be seen around the subducting slab area.
In the western Pacific Ocean, fastest anomalies are not beneath the oldest seafloor region but beneath southeastward of the Shatsky rise.
Depths of negative peak of velocity gradient, which may be used as a proxy to the depth of lithosphere-asthenosphere boundary, have an age-dependence in young seafloor but is about 80 km in old seafloor (older than 100Ma).

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Shear-wave Splitting in the Crust and its Tectonic Implications

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Shear-wave will split into two independent components with almost orthogonal polarizations, when it propagates through anisotropic media. The polarization of fast shear wave (PFS) is parallel to the strike of the cracks, as well as the direction of maximum horizontal compressive stress. Therefore the polarization of fast shear wave can be adopted to study stress in the crust. Stress can influence crack density and aspect ratio of cracks in the crust. The time-delay of slow shear-wave suggests the anisotropic degree and stress status. However in many typical tectonic zones, the crustal anisotropy, especially the PFS, is strongly changed by local tectonics, such as faults.

In North China zone, seismic anisotropy from shear-wave splitting in the crust show strong relationship to faults. PFS on the fault is always parallel to the strike-slip faults. However in the zone away from faults, PFS turns to parallel to direction of maximum horizontal compressive stress.

In northeastern margin zone of Tibetan Plateau, PFS suggests the influence both from stress field and from strike of tectonics/faults. However, in southeastern margin zone of Tibetan Plateau, PFS clearly indicates consistent to crustal deformation, as well as corresponding to GPS data. In both zones, seismic anisotropies in the crust are quite different with those in the upper mantle.

In zone of typical thrust fault, Longmenshan faults, where Wenchuan 8.0 magnitude earthquake occurred in 2008, we found the crustal anisotropy almost is not changed by the thrust faults. PFS is only parallel to direction of maximum horizontal compressive stress. But it shows the influence from faults in the zone away from pure thrust fault. The anisotropic pattern in the crust is different in the upper mantle.

In this study, we discuss shear-wave splitting of local seismic wave and analyze seismic anisotropy in the crust and its tectonic implications. Furthermore we compare seismic anisotropy in the crust and in the mantle.

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Multi-scale Structure and Lithospheric Discontinuities

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The continental lithosphere is heterogeneous on a wide variety of scales and apparent seismic discontinuities arise from the interaction of the seismic wavefield with multiple-scale features. In consequence the character of such discontinuities is frequency-dependent, and interpretation in terms of simple structures can be misleading. Nevertheless it is possible to track discontinuities within the lithosphere across closely spaced stations exploiting P-wave reflectivity extracted from stacked autocorrelograms at each receiver.
Although most inference of finer-scale structure is indirect, corroborative evidence comes from the geochemistry of xenoliths across southeastern Australia. There is a close correspondence between changes in chemistry and P-wave reflectivity in the neighbourhood of the xenoliths.

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On the feasibility and use of teleseismic P-wave coda autocorrelation for mapping shallow seismic discontinuities

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Seismic body waves from distant earthquakes which propagate near-vertically beneath recording stations, provide tools for imaging shallow Earth structures with high vertical resolution. The most commonly used techniques such as P- and S-wave receiver functions utilize conversion mode from P- to S-waves or vice versa to retrieve information on the gradients of elastic properties in the crust and upper mantle. Here we demonstrate the feasibility and advantage of utilizing reflection signals through an improved method of teleseismic P-wave coda autocorrelation. We recover clear reflections independently on vertical and radial components, which provides complementary constraints on the subsurface structures. Field data from different geological settings: from ice-covered stations in Antarctica to bedrock stations on the Kaapvaal craton in South Africa were analyzed. The results from analyses show the feasibility of the method to unveil P- and S-wave reflection signals from shallow interfaces and the Moho discontinuity. The method holds the potential to be applied globally to enhance crustal structure in various geological settings.

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Estimating geophysical model uncertainties in testing procedures versus geodetic data

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Estimating geophysical model uncertainties is crucial in order to properly compare models prediction with geodetic data. Usually, model uncertainties are disregarded and this leads to biased results. In this work, a method for defining the uncertainty of a geophysical model is presented. The empirical covariances of the model-derived quantities are estimated via a numerical procedure and fitted with proper covariance functions that are then used to compute the covariance matrix associated with the model predictions.
The proposed method has been tested in the Mediterranean area. The model's estimated tectonic strain pattern due to the Africa-Eurasia convergence in the area that extends from the Calabrian Arc to the Alpine domain is compared with that estimated from GPS velocities while taking into account both the model uncertainty and the covariance of the GPS estimates.
By considering the estimated model covariance in the $\chi 2$ testing procedure lower test values closer to statistical significance were obtained. Also, through these values a sharper identification of the best-fitting geophysical models was made possible.

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The Mid-lithosphere discontinuity beneath North China Craton

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We image the mid-lithosphere discontinuity (MLD) beneath North China Craton (NCC) by a novel approach — seismic daylight imaging (SDI), which analyzes P reflectivity extracted from stacked autocorrelograms for teleseismic events recorded by several dense arrays. These linear arrays across NCC have average station interval of about 10-15 km, and was deployed by Institute of Geology and Geophysics, Chinese Academy of Sciences under North China Interior Structure Project (NCISP). With higher and broader frequency band (0.5-4Hz) than used with receiver functions, the SDI approach reveals finer scale components of multi-scale lithospheric heterogeneity beneath NCC, which underwent lithospheric destruction in the eastern NCC and seemed to be stable in the western NCC, but with locally lithospheric modification.

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Integrating seismological and satellite gravity data for consistent 3D Earth models

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Satellite data are an ideal tool for global modelling due to their spatial and temporal resolution. For example, the characteristics of satellite gravity gradients allow in combination with seismological models to study the lithosphere in a consistent manner with great detail, which is one of the aims of the ESA STSE “3D Earth".

In the integration of seismological models and satellite observation towards a consistent image of the crust and upper mantle in 3D certain challenges arise. For example, the consistency in resolution and accuracy of seismological and density models is often not provided. The spectral content of the models does not necessarily agree and there is a need for establishing common frames for joint analysis.

We discuss the limitations and sensitivities of different geophysical methods in the context of their imaging capability and in combination for forward and inverse modelling of the Earth's internal structure. Such analysis is the first step to assess the role and feedback of isostatic (lithospheric) and dynamic (deep Earth) effects in shaping the surface of the Earth.

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Tectonic Implications of Lithospheric Attenuation Models

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The majority of studies of the earth's lithosphere have focused on travel times and velocity structure. Less common, but perhaps more insightful, are analyses that center on its attenuation structure. For several years, we have been developing attenuation models of the lithosphere in different parts of the world (Pasyanos et al. 2009ab; Pasyanos, 2013). We employ a multi-phase attenuation where the amplitudes of regional phases Pn, Pg, Sn, and Lg are simultaneously inverted for Qp and Qs of the crust and upper mantle. While this technique has been applied globally, we will mainly focus on the high-resolution models in Eurasia and North America. The resulting models are sensitive to temperature variations and heat flow which is readily seen across the Trans-European Suture Zone and between regions east and west of the Rocky Mountains in North America. Particularly interesting are areas where we see contrasts between Q in the crust and upper mantle, like the Arabian Shield where we see a high Q cratonic crust overlying low Q upper mantle from the Red Sea Rift. Besides tectonic interpretations, attenuation models are used in a variety of applications including accurate magnitude estimation, explosion monitoring (discrimination and yield), and for strong ground motion and seismic hazard.

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Lithospheric structure beneath Thailand as revealed by seismological approach and its future study with Thai Seismic ARray (TSAR)

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Seismological methods have been applied to regional seismic data to study the crust and upper mantle structure beneath Thailand. Receiver function and ambient noise tomography reveal the physical characteristic of crust in each terrane. Crustal thickness beneath Thailand increase from west to east with the average crustal thickness of 30.8 km for Sibumasu terrane (SBT), 33.1 km for Sukhothai Arc (SA), 36.2 km for Loei-Phetchabun Fold Belt (LPF) and 38.2 km for Indochina Terrane (IT). All terranes in Thailand have Poisson's ratio (0.24-0.25) lower than the global average (0.27). This suggests that Thailand might underlie by relatively high-grade metamorphic rock and/or abundant in a felsic composition. Surface waves group velocity tomography from ambient noise period 6-20 seconds show low velocities anomalies in IT and SA. In opposite, ST and LPF have a high- group velocity. The similarity of SA and IT support the geological hypothesis that SA was rift apart from IT during the subduction process, thus they have a similar crustal characteristic. From teleseismic travel time anomalies, upper mantle velocity beneath Thailand can be estimated to increase from west to east. The time-to-depth migration of receiver function data shows no significant variation in the mantle transition zone (MTZ) topography and thickness across Thailand. The MTZ thickness is close to global average with values of 245-250 km. The variation of the mantle beneath Thailand is then likely to be confined in only lithosphere but not an asthenosphere. However, it is difficult to examine whether this feature is control by recent activity such India-Eurasia subduction slab or it is controlled by their own lithospheric origin. From the end of February 2017, forty broadband seismometers of Thai Seismic Array (TSAR) will be installed cover area of Thailand. The resolution analysis of surface wave tomography and body wave tomography from this new array will be present.

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Crustal anisotropy in different tectonic regimes inferred from the stacking of radial and transverse receiver functions

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The H-κ-stacking algorithm of Zhu and Kanamori (2000) is a standard tool to infer the thickness of the crust, H, and the average P to S-wave velocity ratio, κ. We extend their method to include anisotropic properties of the crust such as the fast-axis orientation, ϕ, and the percentage of anisotropy, a (Kaviani & Ruempker, 2015). The inversion involves the computation of theoretical arrival times and amplitudes for up to 20 converted phases instead of up to 5 phases in the isotropic case. These calculations are based on solving the eigenvalue problem of the anisotropic system matrix defined by Woodhouse (1974).

In the stacking algorithm we sum the amplitudes of radial and transverse receiver functions, for all events at the computed anisotropic arrival times. The stacking is performed for simple crustal models and by systematically varying the crustal parameters. The maximum of the stacking function is obtained for the model that is characterized by the parameters (H, κ, ϕ, a) that best explain the observed receiver functions. Application of the method to complex data sets requires additional steps to stabilize the inversion process. For example, the uncertainty of the results is estimated statistically using a selective bootstrapping analysis which only considers solutions that allow to minimize the energy on the transverse receiver-function component when applying an inverse operator to remove the effect of the shear-wave splitting.

We apply the method to recently collected data from permanent seismic networks: (1) strong anisotropy in the crust has been reported previously for seismic stations in Israel (Ruempker et al. 2003); (2) data from the permanent Swiss network will be analyzed as part of the ongoing AlpArray project; (3) an automatization of this method for its application to large data sets is currently being addressed.

We discuss our results regarding the influence of different tectonic processes on the anisotropic properties within the earth's crust.

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Active magmatic underplating in an intraplate setting: combined seismic, seismological, and isotope study in the western Eger Rift, Central Europe

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The Eger Rift is an active element of the European Cenozoic Rift System. It is associated with the intense Cenozoic intraplate alkaline volcanism and system of sedimentary basins. The intracontinental Cheb Basin at its western part displays concurrent geodynamic activity with fluid emanations, persistent seismicity, Cenozoic volcanism, and neotectonic crustal movements at the intersections of major intraplate faults. The CO2-rich gases have increased helium isotope ratios evidencing their lithospheric mantle origin. Active and passive seismic data show increased lower-crustal velocities, which points to the magmatic addition at the base of the crust and to a concept of magmatic underplating. However, character of the seismic image differs laterally, which enables to differentiate two types of the magmatic underplating related to its different timing and tectonic setting. High-velocity lower crust with increase seismic reflectivity evidences the first type of magmatic underplating related to Variscan or pre-Variscan age westward of the Eger Rift. High-velocity reflection-free lower crust together with a strong reflector at its top at depths ~28-30 km forms a lower-crustal magma body. Lateral extent of this body correlates with the distribution of mantle-derived fluid emanations at the surface. Thus, seismic and seismological evidence of the crust/mantle Moho transition supplemented by gas-geochemical investigation and xenolith studies from corresponding depths indicate the second type of magmatic underplating of the Late Cenozoic to recent. Finally, different behavior of fluids in the Cheb Basin with the highest isotope mantle fractions together with Quaternary volcanism points to the ongoing magmatic activity within the broader Late Cenozoic magmatic body and its reactivation in the last 0.3 Ma during Mid Pleistocene to Holocene.

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Formation of the Earth's lithosphere - asthenosphere surface initial heterogeneities.

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The present interface between lithosphere and asthenosphere has a relief surface, as it is indicated by seismic and electromagnetic survey. This relief was formed over a long geological history of the planet. To understand the evolution of these structures it is needed the information about the initial state of the system, i.e., the state at the final stage of the Earth's formation. Here are presented the results of numerical modeling of non-uniform temperature distribution inside the three-dimensional model of the growing Earth at its final stage of dynamical formation. Namely those are heat and matter heterogeneities as objects that are recorded by the results of modern geophysical and geochemical studies. The simulation takes into account the random distribution of the falling bodies and particles, which are falling from the protoplanetary cloud. They are forming the initial distribution of temperature and composition heterogeneities. The evolution of heterogeneities during time is traced by using the numerical solution of boundary problem for a system of differential equations describing the change in mass of the growing planet using Safronov equation, matter flow using Navier-Stokes equations, movement of phase boundaries with use of Stefan problem. As it can be seen from the numerical results of the system solution, to the end of the planetary accumulation it is formed a relatively non-uniform thin crust and inside the upper mantle-the asthenosphere layer. In the mantle it is able to trace heterogeneous inclusions with sizes from the first to a few hundred kilometers with a complex interface. The upper boundary of the crust has also a complicated relief. The formed non-uniform thermal inclusions contribute to the formation of early bottom and upper mantle plumes. The dynamics of these plumes provide special metallogeny of cratons, which is no longer repeated in the geological history of the planet.
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Oceanic Lithosphere-Asthenosphere Boundary Estimated from Stress Dependent Deformation after the 2012 Indian Ocean Earthquake

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Plate tectonic constitutes of a strong lithosphere overlying weaker asthenosphere. Therefore, the structure of lithosphere-asthenosphere system is essential key element to understand evolution of the earth. However, the boundary between oceanic lithosphere and asthenosphere under ocean are remaining poorly understood. On April 2012, an exceptionally large earthquake release high stress beneath Indian Ocean (> 17 MPa in average) during Mw8.6 mainshock and Mw8.2 largest aftershock. This high stress released in wider area of oceanic plate and reached more than 1 MPa in several hundreds depth km of mantle. The 2012 Indian Ocean earthquake, which occurred in the oceanic plate, provide strong constraint of oceanic lithosphere-asthenosphere rheological structure beneath ocean. Here, we try to reveal rheological structure including water content of hot asthenosphere and thickness of cold lithosphere. The boundary between lithosphere and asthenosphere is assumed to be dry olivine in the lithosphere and wet olivine in the asthenosphere as suggested by Karato (2012). Therefore, we develop heterogeneous three-dimensional spherical earth finite element models. The models produce spatial-temporal evolution of stress dependent deformation after the 2012 Indian Ocean earthquake using power-law rheology based on a thermally activated flow law obtained by rock experiments. We propose a systematic grid search to obtain trade off between water content and thickness parameter by using Global Navigation Satellite System (GNSS) data mainly in Sumatra and surrounding Indian Ocean region. In addition, we also investigate a possible stress dependent postseismic deformation mechanism due to the 2012 Indian Ocean earthquake between viscoelastic relaxation, afterslip or multiple mechanisms.

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Seismic constraints on thinning of continental lithosphere beneath the Korean Peninsula: A possible link to oceanic slab subductions and mantle transition zone heterogeneities

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High-resolution structures of the entire lithosphere and the upper part of asthenosphere are investigated beneath northeast Asia using independent seismic data and methods. First, three-dimensional shear-wave velocity structures are estimated from transdimensional Bayesian inversions using ambient noise data. Second, a stacking analysis of multi-mode receiver function waveforms are performed to detect spatial variations of seismic interfaces, including Moho and lithosphere-asthenosphere boundary (LAB). The imaged structures from two analyses are compared to confirm highly reliable features. We observe a dipping trend of the LAB to the center of the southern Korean Peninsula (KP) from the continental margin. In addition, more heterogeneous undulation of the lithosphere thickness is shown beneath the northern KP and northeastern China, where rifted basins and intraplate volcanoes are located. We interpret the observations as a thinning of the lithosphere by interactions with extended sub-lithospheric low velocity structures from back-arc regions of Pacific and Philippine-Sea plate subductions (Kim et al., 2016). We further explore a possible relationship of the lithospheric structure to newly observed heterogeneous structures in the upper mantle transition zone (Tauzin et al., unpublished manuscript).

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Lithospheric Density Structure of Northwest India

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Northwest India is an amalgamation of diverse geological terranes, evolved during past geological periods. In order to comprehend plausible geodynamic models, which can explain continental evolution in the northwest India deep lithosphere density structure of an area encompassing 200 to 300N latitude and 680 to 780E longitude is derived from the integrated modelling of gravity and geoid anomalies and topography and heat flow data. The derived model is well constrained by available seismic Moho depth. Model shows that the Moho depth varies from 34 to 38 km in Saurashtra and Kachchh region, which increases gradually to about 42 km beneath the Jaisalmer region. The deepest Moho at about 50-53 km is found under the Indo-Gangatic plain. A uniform crustal thickness of 40-43 km is observed beneath the Bundelkhand craton. The depth of lithosphere-asthenosphere boundary (LAB) is 110-125 km under Saurashtra and Kachchh regions which remains same under Barmer basin. A moderate LAB under the Aravalli-Delhi fold belt is observed at a depth of 120-140 km. The LAB depth increases up to 195 km below the Indo-Gangatic plain whereas in Bundelkhand craton the LAB depth ranges from 130 to 155 km.

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Azimuthal anisotropy in the Northwest Pacific oceanic lithosphere inferred from Po/So waves

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Po/So waves, which have a high frequency, large amplitude, and long duration, propagate for large distances across oceanic lithosphere. These waves are generated by multiple forward scattering of P- and S-waves due to small-scale heterogeneities in oceanic lithosphere and P-waves trapped in seawater. To study the origin of such small-scale heterogeneities, we analyzed the azimuthal anisotropy of Po/So waves propagating.

Shito [2016, JPGU Abstract] examined the azimuthal anisotropy of Po/So wave propagation using seismic waveform data recorded at Broad Band Ocean Bottom Seismometers (BBOBSs) in the Northwest Pacific from 2010 to 2014. They determined travel times of the Po/So waves using an auto-picking algorithm based on an AR model, and estimated the average velocities of the Po/So waves between sources and stations. The average velocities of the Po/So waves traveling in the Northwest Pacific show clear variations as a function of azimuth, as follows:
$VPo = 8.25 + 0.20 \cos 2(x - 153)$,
$VSo = 4.71 + 0.04 \cos 2(x - 159)$.
The magnitudes of the anisotropy for Po and So waves velocities are 2.4% and 0.8%, respectively, which are smaller than the results of previous studies for Pn and Sn waves [Shimamura, 1984; Shinohara et al., 2008]. The fast direction is parallel to the past spreading direction of oceanic crust as estimated from magnetic anomalies [Nakanishi et al., 1992], which is roughly consistent with the previous studies [Shimamura, 1984; Shinohara et al., 2008].

In this study, we conduct Finite Difference Method (FDM) simulation of seismic wave propagation. We compare calculated and reported azimuthal anisotropy of the Po/So waves propagation and discuss the mechanism, which should be relating to the generation and evolution of the oceanic lithosphere.

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The shear-wave splitting in the crust and the upper mantle around the Bohai Sea, North China

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Bohai Sea area is a significant area with intense deformation in the eastern North China Craton, where experienced thermotectonic reactivation and destruction during the Late Mesozoic–Cenozoic. In order to infer the distribution of local stress and the deep geodynamic process in North China, this study detects first-order seismic anisotropy in the crust and upper mantle beneath Bohai Sea area. We collected local earthquakes within ML4.0 around Bohai Sea area and teleseismic events with magnitude greater than Ms5.5 between August 2007 to July 2012 by shear-wave splitting system analysis method and the grid searching method of the minimum tangent energy to measure the anisotropic parameter. The total 535 local shear-wave and 726 XKS splitting measurements were obtained from stations involving permanent regional seismograph networks and a temporary seismic network. The dominant orientation of local shear-wave splitting in the curst is nearly East-West, which suggests the direction of local maximum compressive stress around the Bohai Sea area. The nearly North-South orientation of polarization caused by structure anisotropy was obtained at some stations, which located at the Tan-Lu fault belt and Zhang-Bo seismic belt. The average polarization of XKS-splitting is 87.4o from north to east. The average time-delays of XKS-splitting range from 0.54 s to 1.92 s, it suggests possibly about 60 km to 210 km thickness of the anisotropic layer. The measured results indicate the upper mantle anisotropy beneath Bohai Sea area, even the eastern of North China, is mainly driven by asthenospheric mantle flow from the subduction of the Pacific plate. From the complicated anisotropic characteristics in this study, we infer that there might be multiply complex mechanism in the crust and upper mantle around the Bohai sea area.

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Effects of random heterogeneity in the upper mantle on apparent radial anisotropy

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Recent progress in seismic tomography and numerical simulations of seismic wave propagation have revealed the nature of heterogeneity and anisotropy in the upper mantle on a variety of scales. Surface wave tomography at lower frequency (5-50 mHz) have shown strong radial anisotropy with faster SH wave speeds than SV in the asthenosphere, particularly in the fast drifting oceanic and continental plates (e.g., Nettles & Dziewonski, 2008; Yoshizawa, 2014). Also, the existence of rapid vertical change of anisotropic properties has been found in continental lithosphere (Yoshizawa & Kennett, 2015), whose depth coincides well with the enigmatic Mid-Lithosphere Discontinuity from receiver functions.

At higher frequency (-10Hz), recent observations of scattered body waves require the existence of horizontally elongated small-scale heterogeneity in the lithosphere (e.g., Kennett & Furumura, 2008, 2013). The effects of such small-scale heterogeneities (correlation distance of kilometer-scale) have generally been ignored in surface wave propagation, whose wavelength is about several hundred kilometers. Such small-scale heterogeneity can, however, cause non-negligible influence on surface-wave phase speeds by changing the effective rigidity of the media and generating “apparent" radial anisotropy (SH>SV).

In this study, we investigate the effects of small-scale heterogeneity on the long-period surface waves through numerical experiments with normal mode calculations as well as 2-D finite-difference method simulations incorporating finely quasi-laminated heterogeneity in the upper mantle. We calculated dispersion curves using a bunch of 1-D velocity profiles including random heterogeneity in the upper mantle. The results suggest that the fine-scale heterogeneity makes the phase speeds of Rayleigh-wave slower, while those of Love-wave faster to some extent, generating apparent radial anisotropy, even though no effect of anisotropy is imposed on the velocity profiles.

Constraints on lithospheric mantle and crustal anisotropy in the NoMelt area from an analysis of long-period seafloor magnetotelluric data

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Despite strong anisotropy seen in analysis of seismic data from the NoMelt experiment in 70 Ma Pacific seafloor, a previous analysis of coincident magnetotelluric (MT) data showed no evidence for anisotropy in the electrical conductivity structure of either lithosphere or asthenosphere. We revisit the MT data and use 1D anisotropic models to demonstrate the limits of acceptable anisotropy within the data. We construct 1D models by varying the thickness and the degree of anisotropy within the lithosphere, and conduct a series of tests to investigate what types of electrical anisotropy are compatible with the data. We find that electrical anisotropy is possible in a sheared and/or hydrous mantle within the lower-lithosphere (60-90 km depth). The data are not compatible with pervasive electrical anisotropy in the crust. Causes of anisotropy within the highly resistive upper and mid-lithosphere, as seen seismically, are not expected to cause measurable impacts on MT response.

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Upper Mantle and Crustal Structure of Sino-Korean and Yangtze Block from Onshore-Offshore Wide-angle seismic surveys

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By combination with other geophysical data, setting active source onshore-offshore wide-angle seismic survey lines in the Bohai Sea, Shandong peninsula and the south Yellow Sea can help us reveal the deep structure of Sino-Korean and Yangtze block, determine the block boundary, obtain the tectonic structure characteristics of the conjuncture of the blocks. In 2010 and 2011 onshore-offshore surveys along two lines in the Bohai area were carried out, these two lines revealed the P-wave velocity (Vp) structure of upper mantle and crust of Sino-Korean. In 2013, another line was carried out, which started from the Bohai Sea area and ended in the south Yellow Sea. By using first arrival tomography and ray-tracing modeling method, we got the Vp structure from Sino-Korean block to Yangtze block. Considering these three lines together, we found that the block boundary is marked by great deep fault zone, the Vp structure is very different from each other on the two sides of the fault zone. The north of Muping-Jimo fault zone belong to Sino-Korean block, where there is no large-scale undulance of Moho. The south of Qingdao-Wulian-Rongcheng fault zone belong to Yangtze block, the thickness of crust is about 32km and the lateral velocity changes smaller than Sino-Korean block. The areas between these two fault zones belong to the suture zone of these two blocks, where the structure is much more complicated. We can find that there is a large scale high velocity zone in the upper crust beneath the Qianliyan uplift and a large scale low velocity zone in the middle crust beneath the Sulu orogenic belt, and the Moho depth increasing from south to north in step plunging, which suggests the process of combination of Sino-Korean and Yangtze block.

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Shallow Moho along the failed rift on the coast of Japan Sea beneath Japanese Islands

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The Mohorovicic discontinuity (Moho) is defined on the basis of an abrupt increase in seismic velocity within the lithosphere observed using seismic refraction and receiver function analysis methods worldwide. Moho depth varies regionally and remains a fundamental parameter of crustal structure. This study presents a new method of mapping the Moho using a 3D seismic tomography model. A zone of high velocity gradient is treated as the Moho because the tomographic method cannot clarify discontinuities. Maximum lower crust/minimum upper mantle P-wave velocities in Japan are known to be 7.0 km/s and 7.5 km/s, respectively. The small residual between isovelocity surfaces of 7.0 km/s and 7.5 km/s corresponds to the high velocity gradient. The best constrained Moho is where the isovelocity surfaces are close together, and under much of Japan, the residual is less than 6 km and rarely larger than 10 km apart. We selected an isovelocity surface of 7.2 km/s as a representative Moho ‘proxy' beneath Japanese Islands. Our resulting Moho map beneath Japan is consistent with existing regional Moho models that were obtained by controlled-source seismic investigations.
The Moho varies from shallow (25-30 km) to deep (> 30 km), and this variability is related to the structural evolution of the Japanese islands: the opening of the Sea of Japan back-arc, ongoing arc-arc collisions at the Hidaka and Izu collision zones, ongoing back-arc extension in Kyushu, and a possible failed back-arc extensional event of Mesozoic age (Matsubara et al., 2017). The Moho along the failed rifts on the Japan Sea side beneath the central Honshu Island is shallow since the high-V lower crust exists there.

Reference:
Matsubara et al. (2017) Configuration of the Moho discontinuity beneath the Japanese Islands derived from three-dimensional seismic tomography, Tectonophysics, in press, doi:10.1016/j.tecto.2016.11.025.

*S21-P-11
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Spatial distribution of the Crust-Mantle boundary in colliding and subducting Izu-Bonin-Mariana Arc beneath Japan using Receiver Function analysis

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Izu-Bonin-Mariana Arc (IBM) is the intraoceanic arc resulting from a subduction of the Pacific Plate (PAC) beneath the Philippine Sea Plate (PHS). The arc has a length of about 2800 km between the Sagami Bay in Japan and Guam (e.g. Stern et al., 2003). IBM collides with the Honshu island at the Izu collision zone and subducts beneath the Eurasian and the Okhotsk plate to the north. The P-wave velocity structure along and across IBM which has yet reached the collision zone revealed a thickened with a width of about 25-30 km (Kodaira et al. 2007). Kinoshita et al. (2015) found a distinct velocity boundary at depths of 40–50 km using the receiver function (RF) analysis below regions where IBM is subducting. They interpreted that this boundary represents the boundary between the crust and the uppermost mantle of the IBM. Furthermore, they supposed the IBM does not subduct to a depth of about 100 km as estimated by tomography. The purpose of this study is to understand the crustal and upper mantle structure of subducting PHS and IBM. To address this, we conduct an inversion analysis of RFs and investigate the seismic structure of the subducting IBM including the distribution of the crust-mantle boundary. In RF inversions, there is a trade-off between the depth of the velocity boundary and the average velocity over the boundary, so we jointly inverted for the velocity structure from receiver functions and dispersion curves of surface waves. Our results are characterized by the following features: 1) The IBM crust is as deep as 40 km below the Izu peninsula. 2) The crust-mantle boundary of IBM discontinuous in the eastern part, whereas continuous in the western part, representing a different style of collision of IBM between the western and eastern part.

*S21-P-12
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Seismological evidence of slab dehydration based on a high-resolution receiver function image of the subducting Philippine Sea plate beneath western Shikoku, southwest Japan

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In the Nankai region, southwest Japan, low-frequency earthquakes (LFEs) are very active at the down-dip limit of the megathrust source region. To reveal the spatial relationship between underground structure and LFE activity, we newly constructed high-resolution receiver function (RF) profiles of the subducting Philippine Sea (PHS) slab and overriding continental plate. In this study, we installed 30 short-period seismographs in western Shikoku for one year. The survey line was aligned in the NNW-SSE, orthogonal to iso-depths of the slab, and it was passed through above one of the dominant LFE clusters. We applied the RF analysis to not only these temporal stations but also nine NIED Hi-net/F-net stations near the survey line. To enhance converted phase amplitudes at a dipping oceanic Moho (OM), we excluded the RFs estimated from earthquakes located in the up-dip direction (SSE) of our survey line. We clearly confirmed the existence of the north dipping OM and the continental Moho (CM) from the profiles. The OM was lying at 30 km depth beneath the Pacific coastline, and inclined to the north with dip of 7-degree. In the northern part of the survey line, the flat CM was located at 30 km depth. At the area where the OM reached 40 km depth, the CM became shallow to the south and gradually unclear. the precisely detected LFEs were distributed to the deep extension of the upper boundary of the PHS slab. The harmonic analysis of RFs implied anisotropic rocks existence just above the OM only at the north of LFE zone. The pressure and temperature there corresponds to the condition for phase transition from blueschist to eclogite with dehydration. Our observation implies that water dehydrated from the oceanic crust rises to the inter-plates, and it causes the LFEs.
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Estimation of global crustal model uncertainty using geostatistical analysis

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Active seismology provides the best tool to estimate the thickness and seismic velocity of the crust. However, seismic experiments are mostly constrained to profiles and hence do not provide spatially complete coverage. Passive seismology can complement active seismology, but is often adversely affected by sparse station coverage, especially on a global scale. As a result, models of crustal properties are based on a form of interpolation, which leads to smoothing and might not reproduce the true crustal structure. This has for example consequences if such models are used to estimate upper mantle densities by stripping of a crustal density structure from the gravity field. The residual gravity field reflects both possible density anomalies in the mantle and the errors in the crustal density model.
Here, we make use of a global database of active seismological data acquired over the last 60 years and explore how interpolation is affecting the attainable accuracy of crustal models and compare our results with previously published global crustal models. Our interpolation method is based on Kriging and provides uncertainties in addition to the gridded values. This uncertainty translates differently to near surface gravity and satellite gravity gradients, which allows to evaluate the uncertainties compared to uncertainties by velocity-density conversion and to define strategies for global inversion.

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Three-Dimensional Seismic Velocity Models of P and S Waves Beneath Western Part of Java, Indonesia from Double-difference Tomography

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Western part of Java is located in active subduction zone where the Indo-Australian plate is subducted under the Eurasian plate. In this study, double-difference tomography has been applied to obtain 3D velocity structures of P and S waves beneath the western part of Java. We have used regional earthquake waveform data taken from the Meteorological, Climatological, Geophysical Agency (BMKG) of Indonesia network from south of Sumatra to central Java. We have re-picked P and S arrival times from about 800 events in the period from April 2009 to December 2015. We have also used additional arrival time data of BMKG catalog for period from January to July 2016. We have selected events which have azimuthal gap < 210 degrees, magnitude > 3, and number of phases > 8. Double-difference tomographic imaging using these data gives a clear velocity structure beneath the western part of Java, especially in the volcanic arc area, i.e. below Mount Anak Krakatau, Mount Salak complex and southern mountains complex in West Java. We observed low velocity anomalies of P and S waves and high Vp/Vs under the volcanoes at depth interval of 80-100 km that may indicate hot partial melting ascending from subducted slab beneath the volcanic arc.

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Heterogeneous structure beneath fault zones of the 2016 Kumamoto earthquake

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The 2016 Kumamoto earthquake occurred in April 2016. The first earthquake (M6.5) occurred at 21:26 (JST) on April 14th. The main shock (M7.3) occurred at 1:25 (JST) on April 16th. The mechanism of this earthquake has a tension axis approximately in the north-south direction and strike-slip fault type. Furthermore, in the Beppu-Haneyama fault zone, located in northeastern part of Kumamoto, induced earthquake (M5.7; reference value) occurred at 01:25 (JST) on April 16th. In this area, there are mainly two active fault zones which are the Futagawa fault zone and Hinagu fault zone. Aso volcano exists in the northeastern part of Kumamoto prefecture, the end of the Futagawa fault zone and it erupted after main shock. The 2016 Kumamoto earthquake is characterized in that the range of seismic activity is very wide and vigorous aftershock activity.
Because the network of seismic stations (58 offline and 13 online seismic observation points) were deployed by Group for urgent joint seismic observation of the 2016 Kumamoto earthquake from April 15, many data of active seismicity were obtained.
We analyzed data of aftershock of the 2016 Kumamoto earthquake. We estimated background structure by comparing the observed envelope with theoretical curve based on multiple scattering model. As a result, there are heterogeneity in the western part of the Hinagu fault zone and beneath the Aso volcano.
As a future task, by comparing the observed envelope with the theoretically expected curve we will estimate the distribution of scatterers based on travel time of the ripples.

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Tectonic Tremor in northern Central Range, Taiwan

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Triggered and ambient tectonic tremor has been observed in the Island of Taiwan, an active and oblique collision between the Eurasian and the Philippine Sea plates. A few triggered tremor sources have been found in norther Central Range but no further details have been reported. Different from regular earthquakes, deep tremor is difficult to detect and locate across a sparse seismic network due to its non-impulsive, low-amplitude property. In this study, we combine four seismic networks operated by different institutes, containing seismic data from tens of broadband and short period stations for average station spacing less than 10 km. We manually detect tectonic tremor through continuous data from 2013 to 2015. For triggered tremor, we examine waveform within 1,200 s after distant earthquakes, epicentral distance more than 1,000 km and magnitude more than 7.5, and 120 s after local earthquakes, epicentral distance less than 100 km and magnitude more than 5.0. We assume tremor only has clear S-wave, use waveform envelope to identify S-wave arrivals, and locate triggered tremor by hypo71. For ambient tremor, we manually check continuous data for extracting tremor events lasting longer than 3 minutes, and apply the same procedure to locate them. Combining the spatiotemporal distributions of the two types of tectonic tremor and local earthquakes, we further discuss the possible mechanism for interactions between earthquakes and tectonic tremor.

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Three dimensional resistivity structure in the source reason of SSEs in Boso peninsula, Central Japan

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We carried out MT surveys in the Boso peninsula (Chiba, Central Japan) to investigate the resistivity structure in the source region of the slow slip events that have occurred at least five times within 20 years. The MT data contaminated by large artificial noise and DC trains showed near field effect at the frequency band below 1Hz. To avoid the local noise, in addtions to the conventional remote reference method, we attempted to apply the independent component analysis (ICA). ICA is one of the multivariate analysis methods and complicated mixing data can be separated into all underlying sources without knowing these sources or the way that they are mixed.
We applied the ICA method to improve horizontal magnetic components in MT data. Two components ICA, using both the data observed in Boso area and the noise free magnetic data observed in Esashi, Sawauchi or Kakioka Magnetic Observatory, was applied for each magnetic component. After the ICA processing, the apparent resistivity and phase were computed by the BIRRP method developed by Chave and Thomson (2004). By this processing, we obtained gentle change and the phases take non-zero values. This result meant that some parts of the noise components such as near field noise were removed.
After obtained the reasonable apparent resistivity and phase, we tried to discuss the 3D resistivity structure using the improved data and discussed the structures in relation to geological structure and the presence of fluid. We estimated 3D resistivity structure using ModEM (Egbert and Kelbert, 2012) . This area is surrounded by the sea and we especially payed attention to effects of the sea. In addition, conductive sedimentary layers widely cover at the shallower depth in this area and the resolution of deeper structure is diminished. We discussed improving of the 3D resistivity structure model under these difficult conditions.

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Crustal structure across the central Ganga foreland basin by magnetotellurics

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The Ganga basin, a foreland basin of the Himalayan collision belt, formed due the flexure of the Indian plate, consists of a thick pile of sedimentary sequence especially in its northern part. Hydrocarbon exploration activities provided the details of the basin architecture and lithologies. However, the structure of the underlying Indian plate is largely unknown despite its important role in influencing the Himalayan tectonics. We acquired MT data along a 285 km long profile at average station spacing of 6 - 8 km across the central Ganga basin to delineate the crustal structure. The profile passes over the sedimentary cover of the basin but at the southern end it covers a part of the exposed Bundhelkhand massif. MT impedance tensors were estimated in 0.001 – 1000 Hz frequency band and decomposed into TE and TM modes by distortion and decomposition analyses. These datasets were jointly inverted along with the Hz data to obtain a geoelectric model of the crustal structure. The results reveal significant variations in the subsurface structure. In the southern segment, the model yields three highly resistive blocks, the southernmost of which correlates with the Bundelkhand craton and extends down to about 150 km while the remaining two blocks are of smaller dimension and buried under the sediments. Based on these results, we infer that the lithosphere of the Bundhelkhand craton is at least about 150 km thick, which is contrary to some previous results suggesting thin lithosphere for the Indian shield. Further, the Bundelkhand craton extends far north of its earlier demarcated position but buried under 0.5 to 1 km thick sediment cover. At the northern end of the profile, an electrically conductive crustal structure has been delineated. In this region, we have earlier reported the presence of thick sedimentary sequence. Thus, our results suggest a highly heterogeneous crustal architecture of the Indian plate in the central Ganga foreland basin.

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Three-Dimensional resistivity structure beneath Payao Fault zone: biggest earthquake in Thailand (5 may 2014)

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Payao Fault zone (PYFZ) is mostly aligned in north-south direction with the length about 90 km cover the area of Chiang Rai, Payao and northern part of Lampang province, Northern Thailand. Base on hazard map of Thailand, this area was classified as risk zone. On May 5, 2014, The biggest earthquake in Thailand with magnitude 6.5 was occurred at Mae Lao district, Chiang Rai province. There were also thousand aftershocks in PYFZ. More than 3500 buildings and a road was damaged. Most of the earthquakes were occurred in the area between two majors fault: the NE-SW-trending Mae Lao Fault Zone and N-S-trending Pan Fault Zone. The focal depth of main shock and major aftershocks were reported at varies depth. The focal mechanisms of main shock and after shock with high magnitude are also reported. However, there are no deep crustal structure in this area. The deep resistivity structure could improve the understanding fault mechanism, geology and tectonic in PYFZ. In order to reveal the PYFZ structure, Magnetotelluric (MT) data from 31 stations as well as a remote reference site at Kanchanaburi province (600 km apart) was installed during February and May 2015. Full impedance tensor with tipper were then inverted to obtain the 3D resistivity structure by using WS3DINV-MPI program. Interesting structures can be observed. Shallow resistivity structure vary from place to place and corresponds quite well with the surface geology. There are is conductor beneath Mae Lao segment (MLS) near the seismogenic zone. The conductor might play an important rule for the 5 May 2014 earthquake and its sequence. It was interpreted as high interconnected aqueous fluid content zone. The fluid in pre-exiting fault, MLS, can reduce the maximum fictional strength resulting the main shock and aftershocks.

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Estimation of electrical anisotropy in the oceanic upper mantle from seafloor magnetotelluric array data

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Electrical anisotropy in the oceanic upper mantle could provide important clues on mantle structure and dynamics if it is confirmed from observational data. Seafloor magnetotelluric (MT) data are useful to estimate electrical anisotropy in the oceanic upper mantle, but should be carefully treated partly because maximum anisotropic signal may not be so large (half an order of magnitude in electrical conductivity) and there is always trade-off between intrinsic anisotropic effects and effects of a large-scale lateral heterogeneity including bathymetric variations and coast effects. One promising method to estimate electrical anisotropy from seafloor MT array data is first to obtain a 1-D isotropic model through iterative correction for bathymetric distortion, and then to estimate anisotropy as deviations from the 1-D isotropic model. We first investigate the performance of this method through a series of synthetic modeling using plausible 1-D anisotropic models for the Normal Oceanic Mantle project area in the northwestern Pacific. The synthetic modeling includes forward modeling using the 1-D anisotropic models with and without bathymetry and inversion with iterative bathymetric correction to data produced from the 1-D anisotropic models underlying a 3-D real bathymetry. After the synthetic test, we apply the method to an observational array data obtained during the Normal Oceanic Mantle project in the northwestern Pacific. We will show and discuss results of the application in the presentation.

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GPS Space Geodesy in Colombia, South America: Velocities and the construction of the Eastern Cordillera of the Colombian Andes

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Tectonic and volcanic activity in northwestern South America is directly related to the interaction of the South America, Nazca, Cocos and Caribbean plates, and the smaller North Andean, Maracaibo, Choco and Panama blocks. In Colombia, the GeoRed network is a dedicated GNSS network for geodynamic studies installed by the Colombian Geological Survey. For this work, using GPS data from nine CGPS sites and twenty campaign sites, a GPS velocity profile across the northeast-trending Eastern Cordillera of Colombia are estimated and compared with results from previous studies based on paleobotanical derived elevations. The geodetic velocities show oblique convergence at 8.8 ± 1.7 mm/yr, consisting of 8.0 ± 1.7 mm/yr of right-lateral strike-slip shear along the mountain range, and 3.7 ± 0.3 mm/yr of shortening. From this, we conclude the following: first, relative movement of the regions east and west of the Eastern Cordillera includes a large fraction of right-lateral shear; second, the convergence rate, the component of velocities west of the Eastern Cordillera relative to those east of it and perpendicular to the trend of the belt is only ~4 mm/yr; and third, at the northeast end of the Eastern Cordillera, shortening is essentially perpendicular to the local trend of the belt, and the highest mountain elevations lie in this region. The strike-slip shear corroborates geologic work suggesting such movement both southwest and northeast of the range. Given the ~200-km width of the Eastern Cordillera, to accommodate ~ 100-150 km of crustal shortening, which has been inferred from balanced cross sections and is implied by recent estimates of crustal thickness, would require ~25-40 Myr of shortening at 4 mm/yr or a complex velocity history. From our results, we can conclude that the present-day GPS velocities are inconsistent with the inference, based on paleobotanical observations, that the Eastern Cordillera rose 1500-2500 m since 3-6 Ma.

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LITHOSPHERIC STRUCTURE IN THE NORTHWEST SOUTH AMERICA FROM RECEIVER FUNCTIONS ANALYSIS

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We have combined seismological data of the National Seismological Network of Colombia for estimating the P to S and S to P receiver functions beneath Colombia and adjacent regions to make a first order approximation of the thickness of the crust and the Lithosphere-Asthenosphere Boundary (LAB) in the NW South America. An iterative time-domain deconvolution process was carried out and then a move-out correction with a time-depth conversion using seismograms of distant earthquakes recorded at broadband stations. P to S receiver functions reveal a relatively thin crust in northern Colombia, with a thickness that roughly varies between 25 and 39 km, with an increase from NW to SE. S to P receiver functions were used to estimate lithospheric thickness, yielding values between 65 and 110 km, also increasing from NW to SE. Lithospheric thickness beneath an oceanic island in the Caribbean is 80 km, whereas for the Ecuador and Colombia Trench is 65 km and around 100 km for the Panama Arc. The transition to the continent is associated with an increase in LAB depth, where it can reach 110 km, with no significant differences among terranes and tectonic blocks.

These results are consistent with the ideas of flat subduction beneath the Colombian Caribbean coast, where a relatively thin continental crust, which gradually thickens toward the SE, is on top of a shallowly subducting Caribbean Plate; the obtained LAB likely represents the base of the oceanic plate beneath the continental crust. The Caldas tear structure may correspond to the southern limit of this plate, where the Nazca plate, appears to subduct with an angle of 34 degrees. This scenario is also consistent with recent observations of teleseismic travel time residuals, which suggest a relatively cold upper mantle, as well as seismic reflection and gravity data.

*S22-1-03
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Arc-arc collision structure in the southernmost part of the Kuril trench region -Results from integrated reanalyse

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The oblique subduction of the Kuril plate is generating a unique tectonic environment in the southernmost part of the Kuril trench area. The Kuril forearc started to collide against NE Japan Arc from the east at the time of middle Miocene to form the Hidaka collision zone (HCZ) in the central part of Hokkaido, Japan. Our integrated reinterpretation for several seismic reflection/refraction experiments revealed detailed and new structural features within the HCZ.
In the southern part of the HCZ, the crustal delamination associated with the collision was clearly imaged by applying CRS/MDRS method to the seismic reflection data (Tsumura et al., 2014). Namely, the upper 22-23 km crust of the Kuril arc is obducted along the Hidaka Main Thrust (HMT), while the lower part of the crust is descending down to reach the subducted Pacific plate.
In the northern part of the HCZ, such delamination structure as obtained in the southern HCZ is not clearly seen. The most important finding in this region is a clear image of the NE Japan arc crust descending eastward to a depth of about 40 km under the hinterland side. Our refraction/ wide-angle reflection analysis revealed the strong dipping reflectors with a velocity contrast of 0.5-1 km/s at depths of 10-35 km just west of the HMT. The obduction of the upper Kuril crust starts at a deeper crustal level of at least 27-30 km and more easterly (~20 km) of the HMT as compared with the case in the southern HCZ. If the metamorphic rocks outcropped east of the HMT are the same crustal materials shallower than 22-23 km depth as in the case of the southern HCZ, the deeper crustal portion originally situated at 23-27~30 km depth must exist in the western side of the present HMT. The very strong and deep reflectors found west of the HMT might result from the mixture of these middle/lower crustal (high velocity) materials of the Kuril arc and upper crustal (low velocity) materials of the NE Japan arc.

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Bookshelf faulting in Iceland: Characteristic of oblique rifts and unstable transforms

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Oblique and immature plate boundaries are frequently characterized by complicated fault patterns, which makes their seismogenic potential and seismic hazard difficult to assess. The structure of the plate boundaries in Iceland is relatively complex. Two of the plate boundary segments are highly oblique to the over-all plate velocity vector between the North America and Eurasia Plates, i.e. the Reykjanes Peninsula and the Grimsey oblique rifts. They contain both volcanic systems and seismogenic strike-slip faults. Oblique spreading leads to extensive volcanism and large earthquakes, a combination that is otherwise uncommon in Iceland. The fissure swarms of individual volcanic systems contain normal faults and fissures, arranged en echelon along the plate boundary. The fissure swarms fade out as they extend into the plates on either side. Overprinting this pattern of volcano-tectonic structures are sets of parallel, transversly striking transcurrent faults that generate the largest earthquakes in the zones, up to M 6.5. Their surface expressions are en echelon fracture arrays and push-up structures. The distance between them varies from 0.5 to 5 km, and together they form a bookshelf-type fault system taking up the shear component of plate movements across the oblique rift zones.
The interaction of the Iceland hotspot with the mid-Atlantic plate boundary leads to frequent ridge jumps by rift propagation and the formation of temporary microplates between the propagating and receding rifts. At present, the Hreppar Microplate is bounded by a transform zone, the South Iceland Seismic Zone, that is the source of many of the most damaging earthquakes in the history of Iceland, up to M 7. The earthquakes occur on many parallel strike-slip faults that are perpendicular to the zone, i.e. by bookshelf faulting. It is postulated that bookshelf faulting is one of the characteristics of unstable or immature plate boundaries.

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Potential for coincident megathrust and crustal earthquakes - an additional component of seismic hazard

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The Mw 7.8 Kaikoura,N.Z. earthquake presents two distinct characteristics to geophysical observers. Seismologically the earthquake is dominantly a megathrust event, apparently part of the southernmost segment of the Hikurangi subduction zone. Field observations show numerous surface rupturing fault segments, many of which show substantial surface offset. This presents the earthquake science community with a dilemma - is the earthquake a megathrust event and the surface faulting a byproduct or is the event primarily restricted to upper plate strike-slip (+ some thrust) faulting? Although seismological analyses indicate some strike-slip-like behavior in the initial and latter stages of the rupture (perhaps as much as 1/3 of the moment), most teleseismic analyses require significant thrust faulting consistent with rupture of the subduction megathrust. Thus it appears that there were synchronous megathrust and crustal faulting events. Similar situations potentially exist along other megathrust systems. Our model that reconciles these two concurrent deformational events includes an inter-seismic period of strain/slip-deficit accumulation along the megathrust plate interface. Co-seismically, crustal deformation conditions are changed by: (a) reduction of fault-normal stresses acting on the crustal faults, and (b) the decoupling of the upper-plate faults from their base (the underlying subducting slab). These effects combine to decouple the faults from their underlying foundation and significantly change the Coulomb stress conditions acting on the faults, allowing appropriately oriented crustal faults to slip concurrent with the megathrust rupture.

*S22-P-01
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Cenozoic rifting and crustal dynamics controlled by Variscan paleoplate boundaries in the mantle lithosphere

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Studies of seismic anisotropy with the use of teleseismic data recorded during the last two decades at dense networks of temporary and permanent stations provided basis for modelling large-scale fabric of the lithosphere–asthenosphere system of Variscan massifs in Europe. Inferences from differently oriented seismic anisotropy image the massifs as mosaics of different microplates that roughly correspond to mapped crustal tectonic units. The mantle lithosphere preserves fossil olivine fabrics of individual domains of the massifs formed before their assembly. Changes of the anisotropy orientation related to boundaries of the tectonic units document rigidity of their mantle lithosphere and a long memory of the coherent olivine fabrics (Babuska and Plomerova, Gondwana Res. 2013). A distinct mantle boundary between the Saxothuringian (ST) unit in the north and the Tepla–Barrandian (TB) and Moldanubian (MD) units in the south, in case of the Bohemian Massif (BM) in central Europe, witnessed a Saxothuringian oceanic subduction followed by a continental collision of the microplates. The suture resulting from the ST/TB collision served as a major Variscan exhumation channel of the HP–UHP rocks. Also the central part of the Cenozoic Eger Rift with a characteristic graben structure developed above this mantle suture. Unlike the HP–UHP rocks exhumed along the ST/TB suture, the Late Cretaceous and Cenozoic volcanic products within the BM follow the broader rim of the ST mantle lithosphere that extends outside of the ST/TB suture (Plomerova et al., G-Cubed 2016). We suggest that younger tectonic and volcanic processes imprinted in the crust are often related to rejuvenated paleo-boundaries in the uppermost mantle. The deep boundaries of the mantle lithosphere domains can be sharp or diffused, depending on how well the microplates were welded into the continental plates.

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Thermomechanical modeling of tectonic inversion at the ocean-continent boundary of the North African margin (Algeria): possible initiation of subduction

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While ocean subduction is one of the most important processes of plate tectonics, the understanding of how and where it begins is still being debated (eg. Gerya, 2011). Northern Algeria is currently undergoing a slow compression deformation due to the ongoing African-Eurasian convergence, as evidenced by active seismic activity recorded both on land and at sea (Yelles et al., 2006). The Algerian margin can thus represent a transitional step between the parameters of active and passive margin (Jolivet et al., 2006). Wide-angle seismic profiles data and The isostatic anomaly models show signs of active or recent compressive deformation along this margin in isostatic desequilibrium. (Hamai et al., 2015). From these observations, two questions: I) What rheological and thermal parameters control the location of compressive deformation at the margin toe? II) Are these parameters suitable for long-term evolution of this margin into a mature subduction zone?
we use the thermo-mechanical code pTatin (May et al., 2014) to test the effect of thermal and rheological parameters on the tectonic inversion of a passive margin characterized by a hot young oceanic area adjacent to a colder continental zone. We consider olso a transition zone (OCT) of 20 km wide between oceanic lithosphere and continental lithosphere, which can be either of oceanic or continental affinity. This OCT can be either vertical or diving towards the continent. Finally, we test the effect of a smooth thermal gradient between the ocean and the continent and a clear vertical line between oceanic and continental geotherms.
Our results indicate that tectonic inversion may evolve towards subduction, when the transition zone plunges towards the continent or towards an indentation of the lower continental crust by the oceanic lithosphere when the transition zone is vertical. In both cases, the strain localization in the margin toe occurs only when it is sufficiently heated by the adjacent ocean area.

*S23-1-01
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Education and Outreach to Foreign Residents Living in Japan- the Importance and Roles of Multicultural Society Coordinators in Creating Systems for Disaster Risk Management Education for Foreign Residents.

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With the increase in the number of foreign residents, Japanese local governments are faced with the task of implementing policies to support them. Establishing disaster risk management policies for foreign residents is one of the most significant points in local government agenda because Japan must confront threats of occurring natural disasters like earthquakes. As a Multicultural Coordinator I have focused on developing disaster risk management education for foreign residents since 2006. Foreign residents are usually not familiar with basic knowledge for disaster risk management or have fewer opportunities to learn disaster risk management because of their limited Japanese proficiency. Therefore it is highly effective and efficient to hold multi-lingual disaster risk management sessions directed solely at foreign residents. On the other hand, it is also necessary to hold disaster risk management sessions where Japanese and foreign residents can communicate with each other in various ways. The first reason to hold these sessions is because the ability to provide multi-lingual information in the aftermath of a disaster will be inevitably limited. And second reason to hold these sessions is because these sessions will boost visibility of foreign residents in the host society which will lead mutual support during a disaster. In the other words, these two kinds of sessions are mutually complementary. The role of the Multicultural Society Coordinator is to create the system in which the foreign residents can learn self-help and mutual assistance in their local societies in Japan.

*S23-1-02
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Global Dynamic Exposure and the OpenBuildingMap - Communicating Risk and Involving Communities

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The substantial reduction of disaster risk and live losses, a major goal of the Sendai Framework by the United Nations Office for Disaster Risk Reduction (UNISDR) requires a clear understanding of the dynamics of the built environment and how it affects the life of communities in case of natural disasters. These dynamics are best understood and captured by local communities, following two of the guiding principles UNISDR formulated: "empowerment of local authorities and communities" and "engagement from all of society". Moreover, communities that participate in risk assessments increase their understanding of efficient risk mitigation measures. Our Global Dynamic Exposure model and its technical infrastructure build on the involvement of communities in a citizen-science approach. Simultaneously, it helps educating community members in the risks they are facing and how they can prevent losses of lives.

We are employing a crowd-sourced exposure capturing using OpenStreetMap (OSM), an ideal foundation with already more than 200 million building footprints (growing by ~100'000 per day), and a plethora of information about school, hospital, and other critical facilities. Besides relying on the very active OSM community, we are providing a tailored building capture tool for mobile devices, facilitating simple and fast building property capturing for OSM. With our OpenBuildingMap system, we are harvesting OSM by processing every building in near-realtime. We are collecting exposure and vulnerability indicators from explicit data (e.g. hospital locations), implicit data (e.g. building shapes), and semantically derived data, i.e. interpretation applying expert knowledge, and translate them into building classifications (e.g. EMS98).

With our tools, interested communities can capture their exposure and analyze how natural disaster will affect them. It helps communicating risks down to the community level and provides the means to involve communities to mitigate risks.

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The research of risk communication using Probabilistic Seismic Hazard Maps

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[Problems]
From 1995, the “Probabilistic Seismic Hazard Maps" (PSHM) has been published every year. This is a distribution map showing the probability of ground motions larger than shindo 6- occurring within 30 years. The purpose of this map is clearly stated as follows; “It is for the public to properly recognize the risk of the ground motion and to promote their disaster awareness and preparation". However, there is no existing research evaluating this map from the perspective of public's better awareness and preparation. We therefore conducted a research measuring the impacts and efficiency of this map.

[Method of Analysis]
Two social surveys were conducted in 2014 and 2015. We first categorized the participants into 3 types according to the probability (High/Middle/Low), and randomly assigned to 4 groups; 1) seeing no maps, 2) seeing PSHM, 3) seeing global hazard map alone, 4) seeing both global hazard map and PSHM. Then we measured their risk perception of large earthquakes, fear, and behavioral intentions to prevent damage.

[Result]
High region participants showed statistically significant improvement in their risk perception and fear by seeing PSHM. Those of Middle region showed no change both in risk perception and fear. For the case of Low region participants, they reduced risk perception and fear by seeing PSHM, which is completely the opposite effect to the purpose of the hazard map.
Another important result is that participants did not intend to prepare more against disaster even in the High region.
Summarizing above, PSHM could improve risk perception only to those live in high probability area, but do not contribute to the behavioral intention for disaster preparation. Those live in low probability area worsen their risk perception by seeing PSHM, while large earthquakes may occur anywhere in Japan. Contrary to its purpose and expectation, PSHM resulted in not a good communication for public's disaster preparation.

*S23-1-04
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"L'Aquila Trial" is a trial of science?

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In the article of Stucchi et al. (SRL, 87, 591-596, 2016), the authors wrote: “All the above cannot but lead one to the conclusion that this was indeed also a trial of scientists and that science was purposely brought into the trial." The prosecution against the defendants consists of a matter of science and a matter of communication. In the Reasons for Judgement ("Motivazione") of the first trial, seventy pages are devoted to the matter of science as written in Stucchi et al., whereas 375 pages of its fifth chapter are mostly devoted to the matter of communication. Noting that the title of this chapter is Causal Relationship ("Nesso di Causalita"), therefore, even in the first trial, more emphasis was put to the matter of communication than to the matter of science. In the sentence document of the second trial (388 pages in total), only 2 pages are devoted to the matter of science. In spite of this situation, at the stage of the prosecution, it was complained to the world that science of earthquake was accused and a campaign was carried out against the accusation. However, this campaign made the families of victims furious because the campaign stressed the impossibility of earthquake prediction while the families' fury was focused on bad communication of the defendants, which they believed to be a main cause of victims' deaths and injuries.

In addition, the article did not mention the responsibility of media, except for the TV journalist who made the “glass of wine interview" and broadcasted it without permission. However, a Japanese documentary program for the L'Aquila Trial showed that another TV station and a newspaper reported the content of the interview in the next morning as it was announced by the scientist defendants. These TV stations and newspaper should be the most responsible for the bad communication. The most important lesson learned from the L'Aquila Trial is that scientists must carefully follow reports released by media on their activities.

*S23-1-05
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InSight/SEIS@Mars Educational program : Sharing the Seismic Discovery of Mars with a International Network of classes

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The InSIght mission will deploy in 11/2018 a suite of geophysical instruments, including 3 axis Very Broad Band Seismometer, 3 axis Short Period Seismometer, 3 axis Flux gate Magnetometer, Heat flow probe, geodetic beacon, infrasound/microbarometer, wind sensors and cameras. As for all NASA missions, children and teenagers will be associated to the K12 InSight program, part of it being associated to the SEIS instrument.
SEIS@Mars Educational project will lead SEIS educational activities and will transmit SEIS data to a network of several hundred of middle and high schools worldwide, associated to existing "seismo(graph) at school" programs in the United States (https://www.iris.edu/hq/sis), France (www.edusismo.org) Switzerland (www.seismoatschool.ethz.ch) and United Kingdom (http://www.bgs.ac.uk/schoolseismology/). The mission website (http://insight.jpl.nasa.gov) and the SEIS web sites (https://insight.oca.eu/ , http://seis-insight.eu) will provide online educational resources.
If the data transmission to SEIS@schools will be automatic after their release by the NASA Planetary Data System, earlier transmission will be made after mid 2019 through the integration of selected schools to the project activities: the selected classrooms will perform the same activities as the project scientists. They will have the chance to process rapidly the proprietary data in order to identify MarsQuake(s) and will will submit requests to the team in charge of processing all requests in order to get the high frequencies events. These schools will fully be associated to the InSight/SEIS discoveries and this will allow the students to perform scientific analysis almost at the same time as the international "professional" seismologists. Although Mars is expected to be less geologically violent than Earth, students with the mission data will be able to perform comparison with Earth and therefore to better understand the difference between our planet and other terrestrial planets.

*S23-2-01
IASPEI Symposium / IASPEI07. Education and Outreach / S23. Geoscience and society

Action research towards effective disaster risk communication

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Action research is one of the characteristic methods in social science. Action research must always take the subtle and complex texture of specific social phenomena into consideration when addressing issues of a practical field. Doing so makes action research more collaborative compared with standard empirical social science: collaboration between outsiders (e.g., researchers) and insiders (e.g., local people), collaboration among researchers representing different disciplines (e.g., between seismologists and psychologists), and collaboration between quantitative analyses which provide overall and general trends, and qualitative, which capture more individual and specific phenomena. I will introduce one example of action research that incorporates both qualitative and quantitative approaches and is applied to the field of disaster risk communication. An App called “Nige Tore," which means “evacuation training," was developed in the aftermath of the 2011 East Japan Earthquake and Tsunami. The “Nige Tore" provides information such as tsunami hazard maps and the lead times before a predicted tsunami arrives at a specific location. During a drill, the “Nige Tore" records user location, evacuation route, and speed through GPS-equipped smartphones. It gives information about whether the individual participant can successfully escape to a safe place from different starting locations and via different routes. The development of “Nige Tore" drills has facilitated meaningful dialogues between developers and users. Research to date has validated the ability of “Nige Tore" functions to facilitate community members' motivation for quick evacuation, and to facilitate the integration of contributions from different stakeholders to co-establish tsunami risk communication system.

*S23-2-02
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Extension of school education for disaster prevention actions over households –a case study of Mashima Elementary School-

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After Great East Japan earthquake, the significance of education for disaster prevention is confirmed further and improvement of current education is highly required at every school. On the other hand, countermeasures against disaster at each household depend on the awareness of parents and so the level of preparedness resulted in large variation compared to that of schools. This represents a severe problem for protecting children's lives because they spend more time at home than at a school. Therefore, education for disaster prevention at school should be designed to have effects over school kids' parents.
This research will discuss a case study of Mashima Elementary School, located in Nagano prefecture. At this school, disaster prevention education was carried out in the means of action research beginning in July 2015 and going into the academic year of 2016. The practice aimed at not only empowering children to save their own lives, but for them to influence their families in taking preventive measures. In particular, the practice consisted of delivering disaster prevention lectures once or twice a year, distributing newsletters every month, and using the newsletters to facilitate monthly disaster prevention classes. As a result, the execution rate of people taking actions such as securing their furniture, significantly increased from approximately 10% to 50%.
This study also indicates its academic significance as it reveals a crucial point of consideration in analyzing results of continuously conducted quantitative research on the same subjects of research. Furthermore, through these interviews carried out on guardians, 20 different factors that may serve as catalysts in encouraging people to actively take part in disaster prevention activities, were discovered. It proved that when empowering people to take action, simply threatening them of risks related to earthquakes is insufficient, but that the effects of these catalysts must be optimized.

*S23-2-03
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An Analysis on The Effects of the Implementation of Short Drills in Taking an Educational Approach to Disaster Prevention - A Case Study of Shirahata Elementary School-

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The occurrence and aftermath of the 2011 Great East Japan Earthquake revealed the significance of taking an educational approach to disaster prevention. Despite the urgency for improvements in taking such approaches, many schools have yet to change.

This research will discuss a case study of Shirahata Elementary School, located in the City of Yokohama. The research began in June 2016, aiming at practicing and implementing effective measures of disaster prevention education. One of the measures of particular focus was the “short drill;" a drill developed as an alternative to conventional evacuation drills lacking in effectiveness. In the short drill, students are divided into two groups and are required to observe each other in reacting to the Early Earthquake Warning. Afterwards, upon the teacher's facilitation, students are to give constructive feedback to each other regarding their actions taken throughout the drill. The short drills were designed to nourish students' abilities in making appropriate judgments that would lead to protecting their lives at the event of a disaster. As such, they were conducted intensively in varying situations during a short time period.

As a result of the implementation, various changes suggesting the effectiveness of the short drills were observed in both the students and teachers. Not only did they become faster in carrying out evacuation procedures, but also displayed the ability to make highly reasoned judgments for their actions.

The utmost goal is for society as a whole to be well prepared for coming disasters. In the presentation, we would like to discuss the effects of the implementation of short drills and by doing so, the presentation will aim at identifying how the empowerment of children through the short drill may achieve this goal.

*S23-2-04
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Adapting the disaster knowledge for the local context – Practices of Tsunami disaster education in Zihuatanejo city, Mexico

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1. Introduction
Disaster education held at school is often given by experts such as researchers (so-called outsiders). On the other hand, the educational contents need to fit with the local context. Because decontextualized education risked learners as, for example, responding earthquake with “drop-cover-hold" was not necessarily adequate under the circumstances of vulnerable buildings of Nepal. Hence, this study analyzes the process of adapting the knowledge given by the author (as expert) for the locality, through the tsunami disaster education for school teachers in two schools of Zihuatanejo city, Mexico.

2. Background of the study area
Zihuatanejo in the west coast of Mexico was historically affected by tsunamis due to the subduction zone known as Guerrero gap. Thus, local administration requested schools to plan for tsunami evacuation. However, the measures were not taken. In this study, two schools which were located in potential tsunami inundation zone were selected and the author intervened to facilitate the evacuation planning.

3. Contents of the education
Two seminars were given to each school. First seminar was to explain the mechanism of earthquake and tsunami and their histories in Zihuatanejo. Second seminar adopted workshop style. Firstly, basics of designing the evacuation route such as “less possibility of road blockage after earthquake" was explained and workshop was held dividing teachers into small groups. Teachers discussed the appropriate evacuation route and shared among teachers afterwards.

4. Analysis and conclusion
Discussed route by teachers were quicker to evacuate and less risk of blockage than the routes which local administration indicated in both schools. Moreover, one school implemented tsunami evacuation drill by teachers' initiatives. Through the observation of workshops, teachers connected the knowledge from expert with the knowledge from local community. This resulted in designing the evacuation route which fit with local context.

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Consideration of the challenges of residents with special needs in tsunami prone area in Japan through implementing indoor tsunami evacuation drills

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After the Great East Japan Earthquake, the needs of Tsunami evacuation drills have been increasing, and various ways of tsunami evacuation drills were developed. Moreover, almost all of the drills developed were implemented outdoor, which train people to move to evacuation sites safety. Survivors needed about 17 to 19 minutes for indoor preparation before evacuation when the Great East Japan Earthquake occurred. However, there were limited numbers of tsunami evacuation drills carried out indoor. The indoor tsunami evacuation is defined as the drills implemented for people to evacuate safely inside their home, such as moving from a bedroom to an entrance where is safer and easier to escape when needed. Therefore, this research examines the indoor tsunami evacuation drills to verify effects of the drills in Kuroshio town, Kochi prefecture, Japan. Participants were selected in the area. This research focused on elderly residents who were reported to have fewer opportunities to participate in general evacuation drills carried out in the area. As a result, the participants were able to arrive at the entrance within two minutes. However, it was characteristic that the speed of moving from one place to another varied by participants and it was observed that some participants needed more time to get up from a chair or bed before moving. This study proved the limit of top-down approach in disaster risk communication due to various needs of participants in disaster situation. Gathering information such as participants' residential environment or individual needs in disaster beforehand enables more effective disaster communication during the evacuation drills. Especially, this bottom-up approach used in this research was observed to be meaningful to motivate elderly residents to prepare for disaster, as the approach is interactive and more inclusive. After the evacuation drills, the participants were observed to have better ownership in disaster risk reduction.

*S23-P-01
IASPEI Symposium / IASPEI07. Education and Outreach / S23. Geoscience and society

Resilience Science for Resilient Society-Real time monitoring, Simulation research, Disaster education -Real time monitoring, Simulation research, Disaster education -Real time monitoring, Simulation research, Disaster education on Resilience Science -

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In Japan and many countries, destructive earthquakes and Tsunamis have occurred frequently.
For early earthquake and tsunami detection, the real time monitoring using ocean floor observatories is effective. DONET1 and DONET2 are in operation and being under constructing around the Nankai trough seismogenic zone SW of Japan, respectively. These systems have multi kinds of sensors such as the accelerometer, broadband seismometer, pressure gauge, difference pressure gauge, hydrophone and thermometer for earthquakes and tsunamis monitoring. DONET1 and DONET2 with 51 observatories will be deployed along the Nankai Trough SW of Japan by the end of March 2016.
Otherwise, to estimate damage of earthquakes and to have images of earthquake and tsunamis, advanced simulation researches are important and indispensable.
Furthermore, we recognize recovers/ revivals are very important and difficult. In Tohoku area damaged by large tsunamis, recovers/revivals have been under progressing after over 6 years passed
after the 2011 Tohoku Earthquake. Therefore, we have to prepare the pre plan before next destructive disasters such as the Nankai trough mega thrust earthquake.

For Resilient Society, Resilience Science including many kinds of fields such as Science, Engineering, Medical and Social Science are significant and indispensable.
Finally, this Resilience Science will contribute to cultivation of human resources.
We will explain the Resilience Science for Resilient Society.

*S23-P-02
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Outreach Programs for school children in India

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The need of the hour is to encourage people to take preventive measures against disasters and also, empower the individuals to take appropriate measures in an event of emergency to save their lives. The approach adopted by scientists is to disseminate intangible information on the up-to date seismological knowledge. However, this is not sufficient as it is repeatedly proved that knowledge alone does not have enough impact on individuals behavioural aspects. Our challenge is to bridge the gap between knowledge and practice by designing an effective Disaster Preparedness Education Program. This should be applicable to other regions in the world, even with different geological, socio-economic and cultural backgrounds. A pragmatic and new approach has to be adopted which are community based understanding of disaster risks and personal empowerment to take preventive actions. In this presentation, the good practices and lessons learned from various case studies in disaster preparedness in Japan, were implemented to Indian scenario by holding workshops jointly by CSIR-NGRI, India, ERI, Tokyo and Keio University Japan at Jawahar Navodaya schools in the Lesser Himalayan Region in North India, under an Indo-Japan collaborative DISANET project Also, we carried forward this program by adopting twin approaches in Uttar Pradesh, Uttarkhand, Jharkhand and Rajasthan where our broad band seismological stations are in operation at Jawahar Navodaya Schools under different scientific programs allowed us to disseminate information on earthquakes and essentials of safety required during an earthquake through examples and empowering the school children for translating knowledge into personal empowerment to undertake preventive actions during disaster.

*S23-P-03
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How do disaster museums communicate with the visitors?

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Disaster education is usually understood as knowledge transfer from experts on DRR to non-experts. However, several preceding studies pointed out this fixed relationship make the non-experts dependent on the expert. On the other hand, it is also argued that collaboration between experts and non-experts is needed to improve the standard of disaster management. In order to tackle this problem, the fixed relationship between experts and non-experts should be changed.
There are thus far 122 disaster education museums in Japan. If the above mentioned fixed relationship is also applied to the museums, there would be no interaction between the museums and the visitors. In order to evaluate current situation of the interaction at the disaster museums in Japan, a questionnaire survey has been carried out. Visitors' feedback has been taken as an example of method of communication between the museums and the visitors. As the result, it is revealed that 57.6% of the respondent museums have at least one method that realise interaction between the museums and the visitors. In addition, it is also revealed that 22.4% of the respondents collaborate with volunteers. This can be understood as another method of mutual communication.

*S23-P-05
IASPEI Symposium / IASPEI07. Education and Outreach / S23. Geoscience and society

How to Facing Disasters? The Meanings of Game-based Disaster Education Tools

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After Japan experienced the 1995 Hanshin earthquake and the 2011 Tohoku earthquake, they realized that it is important to learn to help themselves rather than rely on government. However, to build empowerment for facing disaster is still a challenge in communities. The one-way transfer approach in tradition makes people to remember the right answer but sometimes leads ineffective results. To counter these problems, we developed the game- based tools of improving two-way dialogue between the public, stakeholders and decision-makers.
In this study, we have conducted two game-based disaster education tools in fields. The one is a card game called “Crossroad “, which is designed to have players make decisions when faced with difficult choices under disaster situations. In this study, we also asked players to create their own “Crossroad" for sharing their disaster experiences. The other one is a smartphone application called “Nigetore", which is a personal tsunami evacuation drill, it shows success or not when players finished their drills.
For evaluating the achievements of this two games, we analyzed the dialogues between the players and stakeholders when we held the “Crossraod workshop" and “ Nigetore drill “ in Japan, from 2015-2017. We found out that through “Crossroad", people in communities who concreated their problems communicated to each other and shared the variety views. Through “Nigetore drill", people understood the tsunami hazard and considered the tsunami risk by themselves. More importantly, during playing this two games, people share their “conflicts" and try to find another idea together. This process makes people face disaster actively. In conclusion, this study showed a two-way approach for local communities to shape decision-making and set the agenda.

*S23-P-06
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Effects of Disaster Structural Understanding on Residents' Behavioral Intention against Disaster -Case of Kanto Tohoku Heavy Rainfall Disaster(2015)-

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This research aims to reveal effects of disaster structural understanding on Residents' behavioral intention. In recent studies, some disaster researches which are based on Behavioral Intention Model (Fishbein & Ajzen, 1975; Ajzen, 1991) pointed out that people don't evacuate from disaster at an early stage of disaster developing process.
Tanaka et al.(2013) suggested that this tendency is caused by disaster fragmented understanding and we should change to disaster structural understanding about disaster developing process. Disaster structural understanding consider cause and effect relationship about some serial events which compose disaster developing process. If we learn this relationship between events, we can anticipate what will happen by a former event or information under disaster developing process. But, recent studies have remained raise this hypothesis and haven't revealed effects of disaster structural understanding on Residents' behavioral intention.
The author surveyed residents' disaster structural understanding about river flood and their actions against disaster in Kinugawa river flood caused by Kanto-Tohoku Heavy Rainfall disaster (2015) by a questionnaire survey for three hundred internet monitor in seven towns as disaster impacted area. All towns are riverside of the Kinugawa River and were at risk of this disaster.
After surveyed, the author categorized respondents for three groups corresponding to their disaster structural understanding level, as high-level, middle-level and law-level. Results show that high-level and middle-level groups get a little disaster information earlier than law-level group. The result of increasing behavioral intention is similar to getting disaster information.
The author suggests that disaster structural understanding is useful for increasing behavioral intention against disaster. We should adopt it to education of disaster prevention.

*S23-P-07
IASPEI Symposium / IASPEI07. Education and Outreach / S23. Geoscience and society

Practices of the disaster prevention education that incorporated the necessity of the kindergarten and nursery school

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We have been performing the practical educations for the earthquake disaster prevention childcare at various kindergartens and nurseries in Japan. Based on these activities, we present the results of the disaster prevention education for infants at some kindergartens and nursery schools in the Osaka and Wakayama prefecture, Japan, and the questionnaire findings for their parents and childcare worker after the practice. These cities are the one of the area where the outbreak of the large-scale disaster caused by the strong ground motion and the tsunami are driven apprehensive in the near future. Therefore, to grasp the situation around of the kindergarten for disaster mitigation is an aim of this study. Based on the practice result of the disaster prevention childcare in such a kindergarten, we are going to improve the earthquake disaster mitigation education for the infants.

*S23-P-08
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The Nicoya, Costa Rica, Mw=7.6 Earthquake :A very successful experience of Scientific and Community organization and Preparation

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On October 5th, 2012 a magnitude Mw=7.6 earthquake expectably occurred under the Nicoya peninsula in NW Costa Rica. In spite of its large magnitude with maximum Intensity VIII of MMI recorded, and its on-land occurrence, this earthquake left no casualties directly caused by its shaking and very little damage was produced. Given the occurrence of large earthquakes in this segment of the subduction zone in 1853, 1900 and 1950, a dense geodynamic control network of seismic and geodetic instruments was installed, over a decade before, to capture the incoming large earthquake. Geoscientists kept the population informed of the seismic potential of the region; the mass media was fundamental in getting this information to every corner of the peninsula. As the stress was building up and this network was recording it, an outreach strategy to prepare the population was carried out by Japanese and Costa Rican emergency planners, together with geoscientists. This initiative was part of the BOSAI project which focused on dissemination of geoscientific result to public in earthquake prone area, an International Cooperation project co-funded by the Japan International Cooperation Agency and the Costa Rica Emergency Commission. As a result of this successful experience geoscientists and emergency officials gained recognition and trust from the public.

*S23-P-09
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Minna de Honkoku: online transcription project of historical earthquake documents

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We have launched Web-based transcription project “Minna de Honkoku" in January, 2017. The URL is https://honkoku.org/. “Minna de Honkoku" is also the name for Web application to realize this online transcription project. The study of historical earthquake is based on historical documents. In Japan, almost all of the documents are written in Kuzushi-ji. Kujzushi-ji is writing style used before ~1900. Since the style is different from that of modern Japanese, transcription is necessary to use the historical documents as data for earthquake research. Catalogs of historical records such as "New collection of materials for the history of Japanese earthquakes" has been published and used for earthquake research. Although huge number of historical documents survives, the majority of the documents left untranscribed. We loaded 114 historical documents included in the Ishimoto correction in Earthquake Research Institute Library, the University of Tokyo. We planned to start the transcription project with historical document describing past earthquakes on "Minna de Honkoku," although the application can be used for any type of historical document. "Minna de Honkoku" consists of viewer of document image and vertical (Japanese-style) editor for transcription. Users can input transcribed texts viewing its image. The ranking of words transcribed is displayed to keep motivation of users. The edit history and online bulletin board are implemented to enhance communication between users. The application is inked to Kuzushi-ji Learning Application, KuLA developed by Osaka University. Transcription has been completed for 29 documents out of total 114 documents in 3 weeks. Total number of inputted character is about 700,000. To finish the transcription of 114 earthquake-related historical document is the main goal of the project. In addition, the Web-based project may attract people who are not interested in local earthquake history and natural disaster.

*S23-P-10
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ENGINEERING GEOLOGICAL APPROACHES TO DEAL WITH GEOHAZARD ASSESSMENT IN SEISMIC TERRITORIES

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The Engineering geological studies carried out in seismic territories are mainly focused on the assessment of co-seismic hazards. They consist on the following issues: 1)Site effects due to strong motion seismic events; 2)Liquefaction potential calculation and its numerical prediction; 3)Dynamic characterization of soil and rock mass behavior through lab and in situ experimental campaigns; 4)Seismically induced landslides in soil slopes. Several approaches and methods can be used to tackle the preceding issues commonly taking place contemporarily at a site. Thus, at those sites where strong earthquakes (with Local Magnitude ML>5) occur multiple hazard scenarios must be considered, according to the recent experiences developed in 2009 L'Aquila earthquake, 2010 Canterbury earthquake and 2012 Emilia Romagna earthquake. For addressing these types of studies multiple types of tools must be performed both through experimental and numerical approachesGeophysicists, geologists, geotechnical engineers are needed to combine expertise and scientific knowledge to contribute to understanding the complex interdependency among simultaneous effects induced by natural phenomena, such as the elastic wave propagation from seismic sources placed in the crust.In this contribution, the first issue of the list is considered. Local seismic response is strongly affected by the surface geo-lithological characters and geometrical setting of sediments overlapping the seismic “bedrock" (Vessia and Russo 2013, D'Intinosante and Vessia 2014). This is especially true in “near field areas" (Vessia et al. 2011, Vessia et al. 2016) that is the main character of the Italian Strong Motion seismic events causing heavy economic losses and several casualties. As an example, the case study of Casentino district (L'Aquila province, Italy) is hereafter considered to show how multidisciplinary tools are combined within engineering geological approaches to draw amplification maps at urban scales.

*S23-P-11
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Integrated Probabilistic Tsunami Hazard Assessment against possible tsunamis along Nankai Trough, Sagami Trough, and Japan Trench

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Last years, we presented regional Probabilistic Tsunami Hazard Assessments (PTHAs) for three coastal zones along Nankai Trough, Sagami Trough, and Japan Trench (Hirata et al., 2014, 2015, AGU; Hirata et al., 2016, SSJ). In three PTHAs, our procedures are follows; (i) we consider all possible earthquakes in the future, including those that the Headquarters for Earthquake Research Promotion (HERP) of Japanese Government already assessed. (ii) We construct a set of Characterized Earthquake Fault Models (CEFMs), for all the possible earthquakes(Toyama et al., 2014, JpGU; Korenaga et al., 2014, JpGU). (iii) For all the CEFMs, we compute tsunamis by solving a nonlinear long wave equation, using FDM, including runup calculation, over a nesting grid system with a minimum grid size of 50 meters. (iv) Finally, we gather excess probabilities for variable tsunami heights, calculated from all the CEFMs, at every observation point along the coastal zone to get PTHA. We incorporated aleatory uncertainties inherent in tsunami simulation and earthquake fault slip heterogeneity in the integration process(Abe et al., 2014, JpGU).
In this study, we integrate three of the regional PTHAs calculated from all possible earthquakes along Nankai Trough, Sagami Trough, and Japan Trench to get a nationwide PTHA. We will make two kind of the probabilistic tsunami hazard map; one is “Present-time hazard map" under an assumption that earthquake occurrence basically follows a renewal process based on BPT (Brownian Passage Time) distribution. The other is “Long-time averaged hazard map" under an assumption that earthquake occurrence follows a stationary Poisson process. A Present-time hazard map, showing the probability that the tsunami height will exceed 5 meters at coastal points in next 30 years (starting at 1st January, 2016), suggests high possibility over 50% along the southern coasts of Shikoku to Tokai region, perhaps due to contribution from the next Nankai earthquake.

*S23-P-12
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What was the difference of local people between the 2016 Kumamoto earthquake in Japan and the 2009 L'Aquila earthquake in Italy?

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Japan Meteorological Agency said smaller earthquake will be happen before the main shock of the 2016 Kumamoto earthquake in 14th April. Italian seismologists and officers were found guilty in 2012 for saying it was safe before the main shock of the 2009 L'Aquila earthquake. Experts mistook foreshocks for main shocks in the 2016 Kumamoto earthquake in Japan and the 2009 L'Aquila earthquake in Italy, however local chose different actions. We will introduce analysis of questionnaires survey from local in our presentation.
In addition, we point out following six for important lessons for future disaster education:
1. Teachers should inform students “Seismology has taught us a lot, but there is still a lot we don't know. Earthquake prediction is not impossible today." in disaster education program.
2. It is difficult for human beings to predict events beyond their experience. We need disaster education to learn living lessons in public schools.
3. It is necessary for students to practice of better decision to survive by themselves through disaster education program.
4. It is difficult for human beings to make use of lessons from disasters in other countries because of an instinct for self-preservation that makes them think disasters seldom occur to them and they can survive if they occur. We have to try to learn from living lessons of the world.
5. It is difficult for human beings to pass down living lessons to future generations over decades. Teachers should introduce both good and bad lessons to students from cases in the world.
6. Human beings usually underestimate the danger because they tend to make judgments based on their own experience. On the other hand, experts tend to avoid risk communication to people for fearing spreading panic. We have to doubt information underestimated.
We introduce new activities as a step forward in International Association for Promoting Geoethics. We translate UNESCO English disaster handbook including lessons in Italian and Chinese.

*S24-1-01
IASPEI Symposium / IASPEI08. International Heat Flow Commission / S24. M
ethods and instruments of experimental geothermics – Application and recent evolution

Thermal properties of mud-dominant sediment from the Joetsu Basin in the eastern margin of the Japan Sea

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Thermal properties (thermal conductivity, heat capacity, specific heat, and thermal diffusivity) of marine sediment are important parameters for estimating the flow of fluid and heat in sediment and modeling thermal structure below the seafloor. Although many thermal conductivity data on marine sediment have been accumulated, there are relatively few studies on heat capacity, specific heat, and thermal diffusivity of marine sediment. In this study, we measured thermal conductivity and heat capacity for mud-dominant sediment recovered from the Joetsu Basin in the eastern margin of the Japan Sea by applying the dual-needle probe method. We also measured physical properties (bulk density and porosity) for the mud-dominant sediment. Thermal diffusivity and specific heat of the sediment were calculated from the measured physical and thermal properties. Using the measured thermal properties of the sediment, we propose empirical formulae for the relationships between thermal diffusivity and thermal conductivity, and heat capacity and thermal conductivity for the sediment in the Joetsu Basin. These relationships are different from those for mud-dominant sediment in the eastern flank of the Juan de Fuca Ridge presented in previous work. We suggest that the differences of the relationships between these areas are derived from a difference in mineral composition, probably mainly in the amount of quartz, between the sediments in these areas. This study was financially supported by the MH21 Research Consortium for Methane Hydrate Resources in Japan.

*S24-1-02
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ethods and instruments of experimental geothermics – Application and recent evolution

Laboratory measurements of rock thermal conductivity and diffusivity by transient divided bar and pulsed needle probe methods

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For the determination of terrestrial heat flow and regarding any aspect of subsurface thermal modelling, accurate information on rock thermal properties is of vital importance. Several methods are available for laboratory measurements of thermal conductivity, while fewer are available for thermal diffusivity, and accurate determinations are not straightforward. We have revisited the classical divided bar and needle probe methods with methodological improvements to measure thermal conductivity and volumetric heat capacity simultaneously, and thereby also thermal diffusivity. The divided bar technique is generalised to the transient case (Bording et al. 2016) and for the needle probe, we apply a pulsed mode. For both methods, measured temperature history is fitted by numerical finite element forward modelling, and sample properties are determined using inverse Monte Carlo analysis. This methodology provides a robust framework for deriving sample thermal properties with associated uncertainty estimates.
A series of synthetic tests were performed, and both techniques were applied for laboratory measurements of various materials including different rock samples. The transient divided bar provides excellent reproducibility and high accuracy. For conductivity the obtained uncertainty may be reduced to 1–3 per cent, and for diffusivity to about 3–5 per cent. The main uncertainty originates from the presence of thermal contact resistance across the internal interfaces in the bar, and they need to be minimized. The pulsed needle probe yields equally accurate values for thermal conductivity. The determination of high quality values of thermal diffusivity requires a dense sampling of the temperature rise function at early times and a very good contact between probe and sample material.

Bording, T. S., Nielsen, S. B. and Balling, N., 2016. The transient divided bar method for laboratory measurements of thermal properties. Geophys. J. Int., 207, 1446–1455.

*S24-1-03
IASPEI Symposium / IASPEI08. International Heat Flow Commission / S24. Methods and instruments of experimental geothermics – Application and recent evolution

Thermal petrophysics in application to hydrocarbon reservoir investigations: Current state of art

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Methods and instruments for rock thermal property measurements developed recently and applied in geothermics have obtained evolution and wide application in investigations of conventional and unconventional hydrocarbon reservoirs. The optical scanning technique provided development of a new thermal core logging method with continuous non-contact non-destructive high-resolution (0.2-2 mm) profiling all full sized core samples along a well. The detailed thermal core logging data provide a well-founded selection of full sized core samples for preparation of core plugs that are studied (1) with a special optical scanning technique at dry state and after their saturation with brine and oil, and (2) with special instruments at elevated temperature and pressure. The additional measurements of the rock thermal properties are performed on small pieces of broken cores with the optical scanning technique if necessary. The measurements on frozen rock samples are possible. Determination of elastic wave velocities, acoustic anisotropy, natural radioactivity, density, total organic carbon, porosity, the thermal properties of rock mineral matrix have became possible from the data inferred from the thermal core logging due to correlations established between the rock thermal properties and other rock properties. Combination of thermal core logging and standard petrophysical logging data has allowed determination of geomechanical parameters – Young's modulus, Poisson's ratio, unconfined compressive strength, etc. – from the new thermal core logging technique results and correlations established. The rock matrix thermal properties can be determined from the thermal core logging as well as from the measurements on core plugs. The results are being applied for basin and petroleum system modeling, hydrodynamic modeling thermal methods of EOR, geomechanical and geochemical modeling, detailed characterization of geological structure of hydrocarbon reservoirs.

*S24-1-04
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ethods and instruments of experimental geothermics – Application and recent evolution

A new probabilistic framework to estimate the information content of industrial bottom-hole temperature data: A case study using the Australian OzTemp dataset

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The industrial drilling for petroleum and minerals resources can provide extensive datasets of bottom-hole temperature (BHT) measurements. These represent a primary source of data for understanding the thermal state of the crust. Unfortunately, they are of notoriously low and varied quality. A new framework is therefore presented here to deal with these uncertainties in a probabilistic manner. The framework focuses on two major components of BHT uncertainties; provenance uncertainties, those related to measurement errors and subsequent correction, and intrinsic uncertainties, those related to data rounding and data entry error. By building an appreciation for the uncertainties inherit in BHT measurements, we are able to estimate the information provided by each datum on the true subsurface temperature.
A compilation of international, data-driven studies is used to identify the broad range of biases inherit in uncorrected BHT measurements, as well as the precision of corrected, drill string test, and equilibrium BHT measurements. To identify the degree and magnitude of data-rounding, a novel approached is developed based on a logical appraisal of the statistical characteristics expected of an unadulterated dataset. Deviations from these expectations reveal the scope of human intervention in the raw data. Synthetic testing suggests that it is possible for this method to accurately estimate both the degree and magnitude of potential data-rounding errors in BHT datasets.
Finally, the framework is applied to examine OzTemp, the Australian industrial BHT dataset. The results identify data rounding to the nearest 5* and 10*C, as well as to the nearest 2*, 5* and 10*F. Individual probability density functions can be created to describe the uncertainty between any BHT datum and the true virgin rock temperature. This framework thereby enables higher levels of precision and accuracy in the interpretation and analysis of BHT measurements than has been previously achieved to date.

*S24-1-05
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ethods and instruments of experimental geothermics – Application and recent evolution

In-Situ Optical Scanning

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Knowledge about the thermal conductivity of rock is essential for accurate design of geothermal plants. Thermal conductivity can be measured in situ, with low precision and coarse spatial resolution, or in a laboratory, where samples are subject to altered conditions and represent only limited sections of the borehole. We developed and evaluated a new technology involving fast, high-resolution and high precision scanning of in-situ thermal conductivity within boreholes. The prototype demonstrated the feasibility of the technology for shallow geothermic wells, with an accuracy of 10%.
The probe is designed for use in open-hole areas of a well. It is fixed and adjusted by a packer system, which consists of fixing, measuring, and centralizing packers (outer casing). Optical sensors are placed in an inner casing in the measuring packer. Pneumatic inflation of the measuring packer purges liquid/mud from the measuring interval; thus, optical scanning is possible in mud filled boreholes. Optical scanning is operated parallel to the borehole axis. A laser heats up the foil of the measuring packer from the inner side, and the heat is transferred to the rock formation by conduction. The laser moves with constant velocity along the profile. An infrared camera and triangulation tool are mounted at a fixed distance to the laser, so that the surface structure and corresponding thermal tail of the wall are scanned. Subsequent data processing leads to the thermal conductivity of the borehole. The probe algorithm enables automatic measurements and corrects for profile and packer rubber foil effects.
Prospecting, the technology can be used in intermediate and deep wells. Furthermore the theories according to Prof. Yuri A. Popov can be applied to measure thermal diffusivity and anisotropy. The tool shows that a tomographic thermal conductivity scanning with shallow penetration depth is possible. Thus, a filter cake and layers of altered rock can be distinguished from original rock.

*S24-2-01
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ethods and instruments of experimental geothermics – Application and recent evolution

The structure of free thermal convection flows in water filled borehole inferred from a laboratory experiment

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One of the main methods of geothermics is temperature measurements in water filled boreholes. Development of modern equipment provides high accuracy, stability, spatial and temporal resolution of temperature measurements and significantly expands the geological applications of borehole temperature data. However, the capabilities of these applications often cannot be fully realized due to the effect of free thermal convection (FTC) of the liquid in the wells. The non-stationary character of FTC leads to temperature variations, which represent a significant source of errors in conducting high-precision temperature measurements.
A new experimental lab method for studying the structure of FTC flows in conditions approached to the borehole's one has been developed. The methods based on infrared thermography of temperature anomalies appearing on the outer walls of the vertical water-filled ceramic pipe, where conditions of FTC are maintained. Upward flow of air from the toroidal heater produces temperature gradient on the outer wall of the pipe. The experiments have shown that when the critical Rayleigh number is slightly exceeded (Ra = 290 - 1000) the flows of thermal convection constitute a system consisting of 2 - 4 helical jets, rotating around a vertical axis. At inner pipe's diameter of 20 mm the helical pitch varies from 140 to 300 mm. Angular velocity of rotation increases from 4 E-3 to 25 E-3 rad/s while Rayleigh number grows from 290 to 1000.

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Geothermal field under development: monitoring using unmanned aerial vehicle (UAV)

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Development of a geothermal reservoir requires a system of wells, pipelines and pumping equipment. Management and monitoring of such system is quite complicated, so, in 2016, a Geoscan 201 unmanned aerial vehicle (UAV) equipped with regular and infrared imaging cameras was used for a survey of the Khankala geothermal field (Chechen Republic, Russia). The reservoirs of the geothermal field are being exploitated with a number of old wells and a newly built (2015) doublet and Khankala Heat Geothermal Plant (KHGP). The survey's goals were: (a) – to locate the leaks of the old wells and pipelines, (b) – to compare an environmental impact of KHGP with and without reinjection of the geothermal fluid, and (c) – to evaluate a capacity of UAV-based monitoring methods for geothermal sites. As a result of the survey: (a) - 13 thermal anomalies have been allocated in the area of about 10 sq.km. Analysis of the anomalies facilitated determination of their sources: fire, pipelines, leaking wells, etc., which was confirmed by a ground check; (b) – temporal and spatial parameters of the heat pollution originated from KHGP without the fluid's reinjection have been evaluated; and (c) - a high potential of UAV surveys for environmental and technological monitoring of geothermal fields under exploitation, and/or development have been revealed. The evaluation of the heat pollution has been studied on the basis of two UAV surveys executed with different regimes of the KHGP's exploitation. As a side effect, possibilities of using the plant as an experimental stand should be underlined taking into count high-level KHGP technologies facilitating the doublet, heat-exchangers, and the regime of the whole geothermal loop management.

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Determination of formation equilibrium temperature and geothermal gradient from temperature measurements in production wells drilled in oil and gas fields

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Several ways to determine the parameters of geothermal field according to the temperature measured in the wellbore are known. One of them is the measurement of temperature along the borehole of special wells (control, piezometric). There is a way based on the registration of non-stationary temperature in the borehole after drilling. The idea of the third method consists of the reservoir fluid flowing temperature is recorded as a function of time during the well test. All these methods have known disadvantages and they can be used only in a small number of wells on the interested oilfields.
We have proposed a method of determining the equilibrium temperature of rocks and geothermal gradient from the measured temperature distribution in the producing wells. These measurements are carried out in large numbers on the being developed oil and gas fields. If the well has a sufficiently long sump (for producers it is more than 10 meters), then near the bottom there is zone with undisturbed geotherm. Rocks equilibrium temperature in this range can be determined with a predetermined accuracy by solving the inverse problem with regard to the speed of device movement and the thermal inertia of sensor. CFD modeling, laboratory experiments and analysis of downhole measurements made it possible to investigate the influence of confounding factors: conductive heat transfer from the working reservoir, a metal casing, free heat convection in the borehole on the distribution of temperature in the sump. Algorithm for correcting the measured temperature along the wellbore is developed. Data on the vertical variation of the thermal properties are used to restore the equilibrium temperature of the rocks outside the borehole sump interval. The paper presents practical examples of using the developed method for the determination of the rocks' equilibrium temperature, geothermal gradients and deep heat flux on the Russian oilfields.

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Long-term measurement of 1m-depth geo-temperature and its relationship with ambient temperature change

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It was in 1951 that a group of geophysicists working on hotsprings completed a very good compilation of 1m-depth subsurface temperature data through four seasons at many locations in Japan. After a long time of lack of such kind of data, a new project has been put forward by Ehara in 2012 to restart systematic measurements of geo-temperature at 1m-depths with a standardized simple thermometer system, intending to observe the long-term change of earth's surface temperature and to look into the evidence of global warming as well as that of heat-island phenomena in the Japanese territory. Within the Kanto Plain area where the latter effect is considered the strongest in the world, we have currently 8 stations for long-term measurement.
The focus of this paper is to examine the change of geo-temperature at 1m-depth as time-series, trying to estimate the thermal property of each measurement site from the relationship between the geo-temperature change at 1m-depth and its major thermal driving force, i.e., ambient atmospheric temperature. Its mathematical formulation has been given in textbooks on geothermics. We can see a clear correspondence between the time-series of 1m-depth geo-temperature which we really observed and that of daily averaged air temperature at the same location, with a certain delay-time. Based on the delay-time and also the amplitude attenuation, we estimate the Effective Thermal Diffusivity (ETD) of the materials beneath the ground surface using the Angstrom method. By picking up variation components having periods of 10 to 20 days, the estimated ETD values range from 3.5 to 7.0 E-7 m**2/s. For longer-period components, such as the annual variation, our observation duration up to now might not be long enough yet. The obtained values of ETD, as well as those of annual mean 1m-depth geo-temperature derived from our work, would also be useful in other studies of geothermics, like the inversion of past climatic change based on deep borehole observation.

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Long-term observations of pressure, temperature and flow rate for deep-sea hydrothermal fluid at the middle Okinawa Trough.

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The middle Okinawa Trough locating along the Ryukyu-arc has several active seafloor hydrothermal fields. Cruise CK16-01 by D/V Chikyu targeted the Iheya-North and Noho hydrothermal fields to comprehend sub-seafloor geological structure and polymetallic mineralization. In this cruise, we installed the Kuroko cultivation apparatus that can monitor fluid pressure, temperature and flow rate of the artificial hydrothermal vent.
In February 2016 during Cruise CK16-01, two Kuroko cultivation apparatuses equipped with P/T sensor, flowmeter and load cell were installed at Holes C9017B and C9024A. In January 2017 during Cruise KR16-17 , two cultivation cell parts including sensors were recovered by ROV Kaiko Mk-IV and R/V Kairei . In this study, we report long monitoring data of hydrothermal fluid for more than 10 months at two deep-sea artificial hydrothermal vents.
Hole C9017B at the Noho site, fluid temperature was constant for 5 months from the beginning of the cell deployment. Then, temperature became decreasing from 75 to 40oC gradually. The day and monthly periodic transition of temperature (the amplitude was ca. 0.3 - 0.5oC) induced by tidal wave was found. Among such periodicity, high temperature peaks coincided with low pressure peaks. Drilling operation at Hole C9017A which is 10 m away from Hole C9017B during Cruise CK16-05 in November 2016 would have influenced subseafloor hydrology and induced sudden temperature and pressure drops.
Hole C9024A at the Iheya-North site, pressure, temperature and flow rate also changed periodically with tidal wave, and maximal and minimal points of flow rate were concurrent with those of temperature. The maximum temperature reached 308oC, which is similar to the value obtained from the ROV thermometer (311oC) at the Iheya-North field. The average flow rate of hydrothermal fluid was ca. 300 L/min and, 9 days later, flow rate became zero, suggesting that the impermeable minerals sealed top of the cultivation apparatus.

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Thermal properties of sedimentary rocks for the Tarim Basin, northwest China

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Thermal properties of rocks are essential parameters for investigating geothermal regime of the sedimentary basins, also playing an important role in hydrocarbon and geothermal energy resources assessment. Tarim Basin that locates at northwest China, just north of the Tibet Plateau, has shown great hydrocarbon resource potential, and is the ongoing target for industry exploration. However, systematic measurement of thermal properties of sedimentary rocks for the Tarim Basin is still rare, making the understanding of thermal regime of this basin not well. Herein we collected 114 samples of sedimentary rocks from this basin and measured their complete thermal properties. Our results show that the ranges (and means) of the thermal conductivity, radiogenic heat production, and specific heat capacity are from 1.000 to 3.000W/m.K (2.446 W/m.K), 0.027 to 2.500 HPU (1.210 HPU), and 0.75 to 1.10 kJ/ (kg.K) (0.863 kJ/ (kg.K)), respectively. The calculated volumetric heat (or thermal) capacity and thermal diffusivity fall within the ranges from 1.61 to 2.79 MJ/ (cubic meters·K) (2.26 MJ/ (cubic meters·K)) and from 0.22 to 3.05 unit (1.11 unit), respectively. In addition, it is found that these thermal properties show great differences in various lithologies; even within the same lithology, the values scatter much. This indicates that the thermal properties cannot be used to distinguish lithology alone in practice. The thermal conductivity increases with increasing burial depth and stratigraphic age, suggestive of the influence of change in porosities on thermal conductivity. The specific heat capacity increases with the elevated temperature from 40 to 100 degree Celsius. Furthermore, strong contrast in thermal properties between salt and other common sedimentary rocks would obviously distort subsurface temperature pattern, which should be taken into consideration in basin modelling.

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Repeated borehole temperature logs: climate or anthropogenic impact?

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More than two decades of the activities of the Borehole Climate Observatory of the Institute for Geophysics in Prague clearly proved that the local urban climate gets substantially warmer by more than 2 K since 1993. A 150 m deep borehole, part of the observatory, has been repeatedly logged since then to trace the corresponding time changes in the subsurface temperature field. Transient components of the individual logs yielded by the functional space inversion (FSI) indicated a strong impact of the down penetrating (climate) warming. Its magnitude exceeded 1.3 deg.C at 20 m below the ground surface and reached 0.7 deg.C at 40 m and 0.15 deg.C at 80 m within years 1993 through 2016. The individual temperature logs were inverted into ground surface temperature (GST) histories, compared with the history yielded by a simultaneous inversion of all obtained logs. Their variations were confronted with the results of the surface air temperature monitoring as well as with the records of the nearby meteorological station. Special attention was paid to the analysis the surface temperature offset, the difference between the near surface air temperature and the “skin" surface temperature. The monitored ground surface temperature series were further used as the forcing function to model the corresponding temperature-depth distribution and the resulting time-variable geothermal models were compared with the measured data. It was proved that the observed warming must have been sizeably affected by the terrain alternations and by an effect of new building erected nearby. Some 30-40 per cent of the observed warming can be attributed to the human activities in the direct vicinity.

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Determination of formation equilibrium temperature from unsteady temperature measurements in wells under drilling

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The temperature distribution recorded in wells corresponds to the equilibrium temperature distribution only the measurements were performed in shut-in wells. In practice the temperature measurements are usually performed in scientific, control, piezometric and idle production wells. To determine the equilibrium temperature of rocks after well drilling completion it is necessary to wait for a long time before the well reaches shut-in state that is possible in very rare cases only.
We have proposed a method of determining the equilibrium temperature of rocks from the unsteady temperature recording within some time interval in a well at drilling breaks or after drilling completion. Determination of the equilibrium temperature is based on the solution of the inverse problem using the developed simulator. The simulator allows to calculate the model temperature distribution in drilling wellbore, provides accounting for spatial variations in rock thermal properties and allows to take into account the history of parameter during the well drilling, such as drilling speed, flow rate and temperature variations of the mud at the wellhead. Recording the temperature variation T(t) in the borehole at a particular depth H versus impermeable zones after drilling completion and comparing it with the model temperature Tm(t), calculated using the simulator for different functions of the equilibrium temperature TG(H), allows to determine the equilibrium temperature of the rocks. The mathematical model developed provides modeling the temperature distribution during the drilling process. Results of the sensitivity study of the model describe the model sensitivity to the uncertainties in the input data. The calculations of the formation equilibrium temperature from the unsteady temperature data recorded in the well after the drilling completion were performed.

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Temperature and heat-flow calculations: about the benefit of well-log based thermal-conductivity profiles

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The calculation of temperature and heat-flow-density profiles in boreholes requires reliable values of rock thermal conductivity with depth. We developed a new approach for the indirect determination of thermal conductivity from standard geophysical well logs, which massively enlarges the available databases of subsurface rock conductivities beyond the usual drill core measurements. This approach results in a new set of predictive equations which overcomes the common limitation of empirical equations to specific rock types or to the region for which they were originally developed.
The new set of prediction equations is universally applicable for all major types of sedimentary rocks (clastics, carbonates and evaporites) and allows calculating continuous thermal-conductivity profiles from different combinations of standard geophysical well-logs (i.e. density, hydrogen index, sonic interval transit time, gamma-ray response, photoelectric factor). The combination of three to five well-log parameters results in absolute predictions uncertainties of <15% on a synthetic test data set and of <20% on benchmark laboratory data (Fuchs et al., 2015). However, mean values for geological formations upscaled from laboratory data can be fitted by well logs with uncertainties of approx. 5-7%.
Based on borehole conductivity profiles from various boreholes, we demonstrate the calculation of temperature and heat-flow profiles with absolute errors <3 degC compared to measured temperature logs along boreholes of several kilometers length.

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Geotherms of the continental crust: ambiguity from experimental P–T correction to thermal conductivity

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Calculation of geotherms, reflecting steady-state heat conduction, is dependent on surface heat flow, the compositional model of the crust, and its thermo-physical properties, such as thermal conductivity (k) and radiogenic heat production (H). Available global geotherms are afflicted with uncertainties associated with the simplification of the crustal model, e.g. from dividing the crust into an upper and a lower crust. Here we address uncertainty in geotherm construction that arises from ignoring the mandatory correction of k for pressure (P) and temperature (T). For this purpose, published P-T relations derived from laboratory experiments up to T of 800 degC and performed with physical-contact methods are applied in geotherm calculation, considering different crustal models. The single P and T correction equations are used in a combined approach. The generalized conceptual geotherm model discussed here considers a surface heat flow of 60 mW/m^2 and a 35 km-thick crust consisting of a 16 km-thick granitic upper crust (k 3.0 W/m/K; H 1.5 microW/m^3) and a granulitic lower crust (k 2.6; H 0.45), which is a scenario used in pioneering works on global geotherms in the 1980s and 1990s. P-T relations applied to k are those developed for typical upper crustal (granitic) and lower crustal (granulitic) rock types. Using those rock-specific relations, T at the Moho would amount to 570+/-15 degC. This Moho T is higher by 40 degC compared to earlier work in which some generalized P-T relation to k is applied (Chapman, 1986; Chapman & Furlong, 1992). The difference to Moho T uncorrected for k is more substantial, on the order of 80 degC. Results imply that the crust is warmer if experimental results on P-T relations to k are considered in geotherm parameterization. The difference between corrected and uncorrected geotherms become more serious for higher surface heat flow and for compositionally more diverse, i.e. closer-to-reality crust, and may well exceed 100 degC.

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Thermal conductivity variation of granites at elevated temperatures

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The knowledge of the downward variation of thermal conductivity (TC) within Earth's interior is an important key parameter to estimate the sub-surface temperature distribution accurately. The depth wise variation is dominantly controlled by temperature and to less extent by the pressure. In the present study, we have measured thermal conductivity (TC) variation with temperature for 20 granite rocks from the Bundelkhand craton (BC), central India, one of the oldest cratons in the Indian shield. The BC predominantly consists of granites and gneisses, covering 80% of its areal extent. In this craton, granites exhibit three different varieties based on their geochemical composition.
Measurements are carried out in the laboratory using a steady-state apparatus (guarded heat flow meter, DTC-300) in the temperature range 25 to 300 oC. Thermal conductivity is measured at an interval of 25 oC between 25 and 100 oC and 50oC between 100 and 300 oC. Studied temperature range corresponds to a upper to middle crustal scenario. We found that for the three varieties of the granites, TC at room temperature varies between 2.3 and 3.4 W/m/K whereas TC at 300 oC varies between 1.9 and 2.2 W/m/K. Drop in thermal conductivity in the studied temperature range is significant (10 to 30%) for the all types of granite rocks. Also, this variations in TC are distinctly different among all the three varieties of granites. Moreover, within each type of granite, the drop in TC with temperature is dependent on their TC at room temp. Thus, the observed large variation in thermal conductivity with temperature indicates that the systematic study of thermal conductivity variation with temperatures for granites is essential for precise estimation of the sub-surface thermal regime.

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FEATURES OF THE TEMPERATURE RECOVERY IN WELL AFTER STOP OF INJECTION/PRODUCTION IN CASE OF RESERVOIR WITH HUDRAULIC FRACTURING

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At the present time problem of temperature field changes in reservoir with hydraulic fracturing is very interesting. The knowledge of the geothermal temperature distribution is very important for interpretation of temperature. For this reason, analysis of temperature recovery process after stop of injection/production in case of reservoir with hudraulic fracturing is necessary. In this work analysis of temperature recovery process are made using numerical modelling. Modelling of temperature changes are made with considering of Joule-Thomson and adiabatic expansion effects, convective and conductive heat transfer. The influence of the length, width of fracture on temperature recovery process are studied. It is shown that the presence of a hydraulic fracture in the formation reduces the recovery time of the temperature in the well.

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ACQUISITION OF INTEGRATED PETROPHYSICAL DATA FROM THERMAL CORE LOGGING AND THERMAL CORE PLUG INVESTIGATION FOR USINSKOYE HEAVY OIL FIELD

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The integrated approach to investigations of the Usinskoye heavy oil field (Timano-Pechora province, Russia) was applied. A continuous high-resolution profiling of rock thermal properties (thermal conductivity, volumetric heat capacity, thermal anisotropy coefficient) on all cores (more than 3 000 samples) recovered from two wells was combined with (1) the thermal property measurements on standard core plugs (1x1 “, more than 300 samples) in four core plug states successively (as-received state, dry, brine- and oil-saturated samples), and (2) processing the thermal property data jointly with the standard petrophysical logging data. The optical scanning technique was used for all thermal measurements on full sized cores and core plugs. The results of high-resolution thermal profiling allowed detailing the porosity variations up to scale of 5 mm. Variations of rock mineralogical composition were defined more accurately from inverse problem solution. Possibilities to determine detailed vertical variations in elastic wave velocities and rock density were established and used for estimation of rock geomechanical parameters and their detailed variations along the wells. The data inferred from thermal core logging and thermal measurements on core plugs provided detailed variations in the thermal properties of rock matrix along the wells. The data are necessary for basin and petroleum system modeling, study of formation geological structure, modeling heat and mass transfer processes in reservoirs at thermal methods of enhanced oil recovery, development of technologies for heavy oil recovery, geomechanical modeling, interpretation of temperature monitoring data during the reservoir heating and heavy oil production.

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Effect of water saturation on the electrical impedance and elastic wave velocity of geothermal reservoir rocks

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The estimation of underground water saturation is essential in geothermal fields, particularly for an enhanced geothermal system (EGS). Recently, electromagnetic exploration using magnetotellurics (MT) has been applied to the geothermal fields for estimating water saturation. However, the relationship between the electrical impedance obtained through this method and the water saturation in the reservoir rock has not been well known. Our goal is to elucidate this basic relationship via laboratory experiments. In the fluid-flow test, at first, reservoir rock samples were filled with nitrogen gas, which emulates the superheated steam observed in the geothermal fields. Then, brine was injected into the samples and its injection pressure was increased and decreased to vary the water saturation in the samples. During the test, water saturation, permeability, electrical impedance (at a frequency of 10m-100K Hz) and elastic wave velocity were measured. As a result of fluid-flow test on andesite (Makizono lava formation, Japan), the electrical impedance dramatically decreased from 100K to 1K Ω because of the brine injection. This remarkable change could be due to the replacement of pre-filled nitrogen gas with the brine. After the brine injection, the electrical impedance decreased with increasing injection pressure (small changes in water saturation) by up to 40%. In the pressure-decreasing phase, the electrical impedance increased with decreasing injection pressure and this electrical impedance was smaller than that observed in the pressure-increasing phase (up to 27%). However, the P-wave velocity was almost constant (less than 1%) at that time. These results indicate that the electrical impedance varied with small changes in water saturation in the pressure-decreasing phase, whereas P-wave velocity did not show any variations. In other words, this suggests that electrical impedance could be sensitive to minor changes in water saturation compared with P-wave velocity.

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Reference framework for crustal geotherms, with constraints based on seismic data for the lower crust

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In the present work, we consider the possibility of setting up a reference framework for crustal geotherms, as a useful tool in comparative studies of heat flow in different tectonic settings. The essence of the procedures for crustal geotherms has already been discussed in many of the earlier geothermal studies, but its implications for setting up a global framework has not so far been explored. Geotherms considered in the present work are based on analytical solution to the standard heat conduction problem in stratified media, coupled with empirical relations between seismic velocities and temperatures at the crust-mantle interphase. Iterative trial and error methods has been employed in establishing successful coupling. A major advantage of this approach is that estimates of deep crustal temperatures may be obtained that are relatively free from the perturbing effects of petrological complexities in the upper crust. It also minimizes uncertainties in downward extrapolation of main model parameters. Results of initial tests, carried out for selected sites in stable continental settings, are found to be in broad agreement with indirect estimates of temperatures obtained in deep crustal studies. Another major aspect of this new approach is that it allows estimation of crustal temperatures and mantle heat flow that has connecting links with seismic data, which is useful in comparative evaluation of geotherms across different tectonic settings. The reference frame works for geotherms could serve as a useful supplement to existing IHFC database.

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Thermal data beneath in and around Japan: What we know and do not yet know

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Surface heat flow provides important constraint on the thermal and chemical evolution of the Earth. General pattern of heat flow distribution in and around Japan had been revealed by the early 1970s, and heat flow data have been continuously updated and improved by adding data. However, the number of heat flow data is limited and spatially very inhomogeneous. To provide an attempt at a higher resolution map of heat flow, thermal conductivities are measured using sampled cores and used from existing and newly collected data. Also since we have published a CD-ROM "Geothermal Gradient and Heat Flow Data in and around Japan" [Tanaka et al., 2004], new data are provided. We plan to update the database including thermal properties.

Meanwhile, there exist many indicators that are proxies for quantifying the thermal structure. One of the promising indicators is the cut-off depth of shallow seismicity. Several studies have been conducted to assess the inverse correlation between the cut-off depth and heat flow, since it has attributed primarily to the temperature. Another indicator is the depth of magnetic sources based on spectrum analysis of magnetic anomaly data. This analysis is still controversial, however, good correlation between estimated depths of crustal magnetic sources and heat flow suggests that this depth may reflect the broad average temperature. We address the advantages and limitations of each data and method.

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Mapping the continental surface temperature of Australia: the surface boundary condition for conductive thermal models

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The mean crustal surface temperature represents an important boundary condition for many geothermal studies. This boundary is particularly important to help constrain the information provided by bottom-hole temperature measurements made in mineral and petroleum boreholes, many of which are shallow in nature, observing relatively small changes in temperature from surface to depth. Onshore, this boundary represents the mean land-surface temperature. A mean land-surface temperature map of the Australian continent has therefore been produced from 13 years of MODIS satellite imagery, for the period 2003-2015. The map shows good agreement with independent methods of estimating average land-surface temperature, including borehole surface-temperature extrapolation and long-term, near-surface ground measurements. The MODIS-based method provides spatially continuous estimates (1km pixels) of land-surface temperature and can be employed in regions free from seasonal ground cover of snow. Offshore, this boundary represents the mean sea-floor temperature. A mean sea-floor temperature map of the region surrounding the Australian continent has therefore been produced from models of pelagic temperature data. The mean thermocline observed through each pixel in these models is extrapolated to sea-floor depth. The use of pelagic temperature models also enables spatially continuous temperature estimates (1/8 degree pixels on-shelf, 1/2 degree pixels across the abyssal plain), that will be applicable throughout the world's oceans. When examined in the context of an extensive real-world bottom-hole temperature dataset, the new maps diminished thermal gradient values up to 10% compared to previous methods.

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Energy Budget of the Global Lands in the Course of Recent Climate Change

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Ground surface temperature variation imposes transient perturbation to the steady state of the thermal field of the uppermost crustal layer, hence, impacts the energy flux across the ground surface. In this regard, continental lithosphere is an important regulator of the energy budget of global climate system. Great efforts have been devoted to detect and attribute the heat content changes of the global oceans and atmosphere. Less well understood is the extent of subsurface warming of the global lands. I examined the annual heat content change of the continental landmasses over the period from 1850 to 2015 based on meteorological records. Result shows that the rocks beneath 30% of the globe has absorbed 19 ZJ (10^21 Joules) of thermal energy since the beginning of the 20th century global climate warming, more than twice as much thermal energy as the entire atmosphere has absorbed. The calculated subsurface temperature anomalies are consistent in general with the anomalies recorded in more than 1000 borehole profiles of the global database of borehole temperatures for climate reconstruction. I further extended the analysis to Year 2100 under three climate scenarios: a business as usual scenario of continuation of the recent warming trend, a climate stabilization scenario with ground surface temperature maintaining at the current state, and an energy freeze scenario of halting the ground surface energy flux. If the observed global warming trend over the 25 year period (1991-2015) is to continue at 2.89K/100a, an additional 51 ZJ of heat will be trapped underground by the end of the 21st century. Even if the global surface temperature is to stabilize at the current state throughout the rest of the 21st century, the continental landmasses will continue to acquire over 15 ZJ extra energy from the atmosphere. An overall 0.72 K cooling at the global ground surface between 2016 and 2100 is required to avoid further heating of the continents.

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evelopment and application of geothermal databases

Development of geothermal studies in Uzbekistan

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A high variability of Heat Flow Density (HFD) is typical for the territory of Uzbekistan. The statistics show that the HFD changes in a wide range from 18 mW/m2 (the site Karamurum in the Central Kyzylkum) to 207 mW/m2 (well Jarkamar in NW Ferghana). Several zones with a thermal flow as high as 100 mW/m2 are distinguished in the SW spurs of the Gissar and Surkhandarya depression. In the Central Kyzylkum, there are 60 points for the determination of HFD, mainly in ore deposits. The limits of changes in the HFD values vary from 18 (site Karamurun) to 90 mW/m2 (deposit Muruntau). Geothermal data such as terrestrial heat flow, temperature gradient and rock thermal properties as thermal conductivity, heat capacity and radiogenic heat production rate of rocks have been investigated by the author (patent Heat Flow_DataBase BGU00339Uz).Laboratory studying of thermophysical properties of rocks. In our laboratory during long-term develop study of thermophysical properties of rocks. On the base of obtained data and raster pictures of distribution of elements in the sample, received on microanalyzer JXA-8800R JEOL the computer program PercolationCheck (the patent DGU 01170Uz) intended for calculation of percolation – high thermal conductivity process in rocks has been developed.

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Temperature and heat flux changes at the base of Laurentide Ice Sheet inferred from geothermal data (evidence from province of Alberta, Canada)

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Using a previously published temperature log of the 2363 meter-deep borehole Hunt well (Alberta, Canada) and the results of its previous interpretation, the new reconstructions of ground surface temperature (GST) and surface heat flux (SHF) histories for the last 30 ka have been obtained. Two ways to adjust the timescale of geothermal reconstructions are discussed, namely the traditional method based on the a priori data on thermal diffusivity value, and the alternative one including the orbital tuning of the surface heat flux and the Earth's insolation changes. It is shown that the thermal regime of the Earth's surface in the area during the last glacial cycle was formed under the influence of a number of factors. These include the orbital related insolation changes, thermomechanical properties of the Ice Sheet, deglaciation, formation of glacial lakes and their subsequent draining. Still, the insolation remains the main factor which determines the behavior of the other factors through a complex system of climate feedbacks.

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Evaluating methods and uncertainties in the inversion of downhole temperature data for palaeoclimate studies, Australian examples

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Downhole temperature data have been used for many years to try and understand variations in ground and air surface temperature in the geological past. The inference of ground surface temperature histories from borehole temperature data is an ill-posed inverse problem that can be approached via a range of numerical methods, broadly divisible into (1) regularisation and (2) Bayesian techniques. Inversion results are dependent on the method chosen and the details of the implementation, as well as the geological constraints built into the inversion. A number of authors have compared different approaches exploring, for example, the impact of variations in geological and geophysical parameters such as borehole depth and uncertainties in measured thermal data on inversion results. We add to this body of work looking at the sensitivity of different inversions of realistic synthetic temperature data. On the basis of this, we invert real temperature data collected from two purpose-drilled and well-characterised boreholes in southeastern Australia: Tynong-1, southeast of Melbourne (total depth of 400m) and Stavely-07, in western Victoria (total depth of 500m). Results suggest that inversion may result in over-interpretation of the data and that it may be difficult to distinguish equally plausible temperature histories.

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A geothermal resource assessment based on GIS analysis of multiple parameters for the Guanzhong Basin, NW China

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The Guanzhong Basin, also known as Weihe Basin, in Shaanxi Province of NW China is a Cenozoic allusive basin of graben origin. It is situated between the Qinling Mountain on the south and Beishan Mountain on the north with an area of about 36,000 km^2. The basin is rich in low to medium temperature geothermal fluids. There are currently about 200 geothermal wells in this basin, tapping hot water mainly from four aquifers at the depths between 400 and 4000 m. Data from multiple sources such as heat flow, borehole temperature, geological structure and stratum, earthquake catalog, crustal electrical structure, remote sensing imagery, and socioeconomic data are assembled into a GIS platform to facilitate better assessments of resource, demand and application potential. Heat flow within the basin varies in the range of 62-80 mW/m^2, with a mean of 71 mW/m^2 which is substantially higher than the regional mean. Based on geological structure, the basin can be divided into six uplift/depression segments. Geothermal resource is found to be most enriched in the Xi'an Depression where the maximum Cenozoic sedimentary thickness reaches 7,000 m. Light to moderate earthquake epicenters are concentrated along the boundaries of the uplift-depression boundaries. With a population of over 8.5 million, the Xi'an - Xianyang area is the most populated and economically developed area in the basin. The abundant geothermal resource is coincided with high demand for renewable energy to sustain the economic and social development in this area. Our analysis shows that geothermal resource can play an increasingly important role in the socio-economic and environmental development of the Guanzhong Basin in general, and Xi'an – Xianyang area in particular.

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Terrestrial Heat flow and 1D Geoelectric Model of the Baiyinchagan Sag, Erlian Basin, Northern China

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The Baiyinchagan Sag is located in the western margin of the Erlian Basin, a Mesozoic rift basin in the collision suture zone of the Siberian Plate and North China Craton in northwest Inner Mongolia in northern China. Here we report preliminary analysis of new heat flow measurements in four deep boreholes and magnetotelluric soundings at these borehole sites. Subsurface temperature gradient varies from 35.6 to 45.4 degrees per kilometer in the selected boreholes between the depths from 200 to 2150 m. Thermal conductivities of 36 sedimentary and metamorphic rock samples fall in the range of 0.93-4.03 W/m/K. The mean of the measured heat flow values is 76 mW per suquare meter. Our new heat flow measurements are consistent with the recent report of Zuo et al. (2016, 75 mW per suquare meter), but substantially greater than the estimates of 43-66 mW per suquare meter registered for the Erlian Basin in the fourth edition of the Chinese heat flow data compilation (Jiang et al., 2016). One-dimensional Occam's inversion of the magnetotelluric sounding data shows that the uppermost 4 km layer of the rocks are low in electric resistivity (<100 Ωm), likely due to the fluid in the porous strata. A high resistance (>2000 Ωm) layer is located at the depth of 7-20 km. We are in the process of constructing the thermal structure of the lithosphere for the Baiyinchagan Sag based on the new measurements and other relevant geological and geophysical data. The geodynamic and petroleum resource implications of the lithospheric thermal structure will be discussed, and the results will be presented at the meeting.

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Shallow crustal heat flow and heat production inversion

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Understanding the heat flowing from the Earth is fundamental to understanding the nature of the crust. Previous attempts to analyse the surface heat flow across the Australian continent have typically interpolated the sparse available data points. These studies inherently make the assumption that lateral distance between heat flow determinations is sufficiently short to act as a proxy for changes in the estimated rate. However, the variations apparent in the data suggest that such an assumption cannot hold. Surface heat flow estimates can be regarded as the sum of heat flowing from several source components. The observation of linear heat flow provinces suggested that, over large distances, the heat production at the surface of the crust provides a first-order constraint on surface heat flow rates. Regardless of the physical mechanisms behind these patterns, this seemed to suggest that the remaining heat flow component, commonly referred to as 'reduced heat flow', exhibits large wavelengths of variation that are, in general, more amenable to spatial interpolation over large distances.
We approach heat flow inversion as regression problem. The reduced heat flow signal is regressed from surface heat flow determinations, where upper crustal heat production provides a purely-additive noise that masks the coherence of the reduced heat flow signal. We use a transdimensional-tree Markov Chain Monte Carlo model to regress reduced heat flow across the Australian continent. Our prior beliefs about the heat production in the upper crust, informed by surface geochemical measurements, enable the two components of surface heat flow to be probabilistically separated. In this format, the noise modelled in our regression can be recovered and represents the total inferred heat production for the shallow continental crust. This method is applied to the Australian surface heat flow dataset, and the results and their uncertainties are presented.

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Magma underplating at crust mantle interphase as the source of anomalous heat flow in passive continental margins

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Analysis of global heat flow data points to the existence of narrow belts of relatively high heat flow (> 60mW/m2) along several segments of the passive continental margins. These belts are confined between zones of low to normal heat flow, present in adjacent stable segments of continental and oceanic crust. Available data on the width of the heat flow anomaly (range of 100 to 300km) precludes thermal refraction effects. Hence, we consider release of heat by sources located at the base of transitional crust as the likely mechanism. Model studies were carried out to examine the nature of magma underplating. The results indicate that an underplating episode at a depth of 20km, occurring 2Ma back in time, is capable of accounting for the observed heat flow anomaly. It is argued that weak "tectonic bonding" between continental and oceanic segments of the lithosphere and ductile nature of mantle at the contact zones allow lateral flow of magma at the base of the crust. This mechanism seems to be an end-member case of differential stretching, in which extension is limited mostly to the sub-crustal layer. However, these need not necessarily produce intrusive or volcanic activity in overlying strata. We advent the hypothesis that passive flow of mantle material at the base of transitional crust is responsible for much of the micro-seismic activity at shallow depths along continental margins. Results of model studies also reveal that a combination of thermal maturity indices and palinspastic reconstructions of sedimentary strata may be used to constrain estimates of the duration of underplating events. Analysis of data for continental margin of Brazil point to the occurrence of two successive underplating events: a recent short-period one to account for the observed heat flow anomaly and an older long-period one for boosting thermal maturity indices to levels compatible with the occurrence of extensive oil fields.

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Two-dimensional thermal modeling associated with subduction of the Philippine Sea plate beneath southern Kyushu, Japan

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There is a non-volcanic region sandwiched between the Aso and Kirishima volcanic zones in southern Kyushu, Japan. Several characteristic seismic events were identified around there; Postseismic slips were found associated with the two Hyuga-nada earthquakes (M6.6), which were interplate earthquakes that occurred on October 19 and December 3, 1996. Tectonic tremors were observed around the mantle wedge corner beneath the Pacific coast of Miyazaki prefecture. To investigate the cause of these events, we performed 2-D box-type time-dependent thermal modeling in southern Kyushu. We set a profile to pass through the regions in the plate convergence direction where tectonic tremors and postseismic slips were identified. To constrain calculated temperature structure, we used surface heat flow data. In our model, we considered the subduction history of the Philippine Sea (PHS) plate, and changed the age of an ocean floor and subduction velocity along the profile at each time step. To explain the observed low heat flow above the mantle wedge corner, we introduced a low viscosity layer at the plate boundary. It became difficult for mantle flow to intrude into the mantle wedge corner, by incorporating the low viscosity layer, and surface heat flow above there became lower than that without it. As a result, the temperature range of the upper surface of the subducting PHS plate where postseismic slip associated with the 1996 Hyuga-nada earthquake on December 3 occurred became approximately 300 degree. Interplate temperature where tectonic tremors occurred beneath Miyazaki prefecture ranges from 400 to 500 degree. We also estimated the dehydration process along the profile and used the phase diagram of hydrous MORB in the oceanic crust. As a result, blueshist transformed into lawsonite blueshist in the postseismic slip region, and lawsonite blueshist transformed into lawsonite eclogite in the active region of tectonic tremors.

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Reconstruction of recent 6Ma thermal structure seaward of updip limit of Nankai seismogenic zone off Kumano inferred from IODP NanTroSEIZE geothermal data and time-dependent numerical model

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Understanding the slip behavior of the seismogenic faults in subduction zones requires accurate estimates on the present & past thermal structures. To depict the thermal history, we need to know the tectonics and thermal regime of the Philippine Sea plate (PHS), which may have stopped subduction until ~6MaBP, and restarted afterwards. Our purpose here is to test if such subduction tectonics can affect the ‘present' thermal regime.
During the IODP NanTroSEIZE expeditions, we deployed 2 borehole observatories containing 5 thermistors. In 2012, the first one was deployed at Site C0002 above the updip limit portion of megathrust, and the temperature and heat flow at ~900 m below seafloor is determined as 38 degC and 57 mW/m2, respectively. In 2016, we deployed the second one at Sites C0010 across the shallow megasplay fault zone. Thermistors are located between ~400 mbsf (crossing the fault zone) and 562.72 mbsf, and the temperature at 562.7 mbsf is 26.7 degC. With core thermal conductivity data, average heat flow is determined as ~60 mW/m2. It is slightly higher than nearby Site C0004 (54 mW/m2). It may be attributed either to pore fluid flow or transient phenomena (e.g., burial due to thrust faulting).
Using these heat flow data, a thermal evolution model around the updip zone of Nankai seismogenic zone is constructed for 2 end-member models; subduction of 12Ma-old Shikoku Basin (SB) started at 6MaBP, vs. subduction of 5Ma-old SB continued since 13MaBP. We found that two end-member models (subduction has been continuous vs. it started 6MaBP) are very similar and impossible to discriminate to each other. We also found that the thermal structure at 6-3MyBP can be different from the present one. In that case the accretionary prism evolution, as reconstructed through paleo-thermometry, may need reconsideration.

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Numerical Simulation of the Geothermal Effect of the Millennium Eruption of the Changbaishan Tianchi (Mt. Paektu) Volcano at Sino-North Korean Border

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The eruption of the Changbaishan Tianchi Volcano (CTV, also known as Mt. Paektu Volcano) in around 1000AD ejected about 100 cubic kilometers peralkaline rhyolites. It was one of the largest explosive eruptions in the world over the last 10,000 years. Volcanic eruptions are associated with a vast amount of heat being carried from the greater interior to shallower depths by magmatism. Therefore, volcanic areas are generally rich in geothermal resource. Numerical simulation is an effective means not only in the research of thermo-tectonic evolution of the lithosphere, but also in the assessment of geothermal energy potential in a volcanic area. Here we simulate the thermal effects of the magmatism with ANSYS WORKBENCH, a finite-element simulation software platform that has been widely used in engineering thermophysics, but so far rarely applied in a geothermal research. Based on the latest geothermal, petrological and geophysical data, we construct two conceptual models to simulate the thermal effects of the CTV Millennium Eruption. Petrological studies indicate that the erupted CTV rhyolites were derived from the upper-middle crust at depths of about 10-15 km; whereas recent magnetotelluric sounding and analysis of Advanced Land Observing Satellite PALSAR data suggests that the magma chamber is located in the upper crust beneath the depth of around 8 km. Consequently, our two conceptual models represent the upper crust and upper-middle crust magma chamber scenarios, respectively. Simulation result shows that in either case, the conductive thermal diffusion of the magma activity of the CTV Millennium eruption 1 kyr ago is restrained within the range of 500 meters from the intruded magma column. This might be part of the reason for the lack of widespread hydrothermal activities in the CTV area.

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Heat flow distribution along the Nankai Trough floor correlated with the crustal structure of the incoming oceanic plate

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Detailed heat flow measurements conducted on the floor of the Nankai Trough, near the trench axis, revealed that the heat flow distribution significantly varies along the trough. The variation appears to be correlated with the spreading history of the incoming Philippine Sea plate (Shikoku Basin). In the central part of the trough (between 134.5 and 136 degE), the youngest part pf the Shikoku Basin formed by spreading in the NE-SW direction, heat flow is highly variable and the average is much higher than the value estimated from the seafloor age. In the older parts of the basin formed by E-W spreading with a faster rate, located on the east and on the west of the central part, heat flow is nearly normal and less scattered. Other geophysical data, e.g., seismicity, crustal thickness, and basement topography, also vary significantly around the spreading direction boundaries. It suggests that the crustal structure changes across the boundaries associated with differences in the spreading direction and rate. The high average heat flow in the central part of the trough floor can be attributed to heat transport along the plate interface by fluid circulation through a permeable layer in the subducted oceanic crust (Spinelli and Wang, 2008). The permeability structure of the crust may be different between the central part and the older, eastern and western parts, resulting in difference in intensity and/or pattern of fluid circulation, and thus the observed contrasting heat flow. The high variability of heat flow in the central part may also be related to the crustal structure. In the central part, characterized by large basement relief, there is a negative correlation between heat flow and sediment thickness; higher heat flow on basement highs, whereas no apparent correlation is found in the eastern and western parts. These findings indicate that the crustal structure of the Shikoku Basin has a large influence on the temperature distribution along the plate interface.

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Modelling three-dimensional hydrothermal heat transport around the Nankai Trough

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To understand the behaviour of mega-thrust earthquakes, estimating temperature structure of the subduction zone is a key issue. The Nankai Trough, with a lot of heat flow data, is one of the best regions for this purpose. The major features of the available data are high heat flow (more than twice that expected from thermal models with the corresponding plate age) at the Muroto area, moderately high heat flow (at most 1.5 times that expected from thermal models) at the Kumano area (150 km east of the Muroto area), and a gradual heat flow variation between these areas with the spatial scale of ca. 50 km.

Spinelli and Wang (2008) proposed a thermal model including hydrothermal circulation to explain the high heat flow at the Muroto area. They assumed that the uppermost 500 m of the oceanic plate (usually called aquifer) is permeable both before and after subduction. This model explains the heat flow data and gives an important aspect that temperature at depth along the aquifer is decreased by 50 degrees Celsius.

Here we extend Spinelli and Wang's (2008) model so that the heat flow variation between the Muroto and Kumano areas can be targeted. We pay attention to hydrological structure of the crust and irregular slab geometry between these areas, which reflects paleo-spreading direction. We construct a three-dimensional model including anisotropic aquifer permeability to include these features.

Results are summarised as follows. 1) Taking a high permeability entire of the areas results in pervasive high heat flow. 2) High permeability at the Murtoto area and low permeability at the Kumano area with a sharp contrast between these areas, results in a sharp heat-flow contrast between these areas. These are not the case. 3) We consider anisotropy in permeability, in which the Muroto area has high permeability and the Kumano area has high permeability only in the direction parallel to the trench axis. This model can explain the heat flow variation between these areas.

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Curie Depth Point of the Iberian Microplate. A thermal, compositional and tectonic perspective of its evolution

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Thermal structure of the Iberian micro-plate is derived from magnetic data through the Curie-Depth Point (CDP) isotherm, which accounts for the depth at which ferromagnetic minerals become paramagnetic (˜580 ºC). CDP modulates the surface heat flow through thermal conduction. Variations on the CDP thickness translate into heat anomalies most probably due to small scale tectonics. The CDP, the CDP derived thermal gradient with the Moho depth maps provide knowledge on the thermal regime. Within Iberia the isotherm is located at depths of 17 to 29 km beneath surface. This isotherm is shallow offshore, where the lithosphere is thinner. In continental Iberia, the Variscan domain reveals a deep signal, probably linked to thickening-extension processes during the orogeny, which an extensive emplacement of granites (in the Central Iberian Arc). This resulted in a very thermally conductive crust. The CDP at the Gibraltar Arc is consistent with the slab roll-back geodynamic model. Offshore the broad magnetization can be accounted for by proposing serpentinization of the upper mantle. Similarly, in the Atlantic margin, a relatively thick serpentine layer is interpreted, which is consistent with a hyperextended margin configuration (exhumed mantle has been sampled). The Mediterranean presents generalized serpentinitation in the Algerian Basin. Furthermore, correlations have been found between the CDP, thermal gradient and vertical ground motion, where subsidence is related to low thermal gradient and, null or small uplift implies high thermal gradient. (Research supports: CGL2014-56548-P, 2009-SGR-1595, CGL2013-47412-C2-1-P)

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Seismogenic Layer within the Crust beneath Japanese Islands on the Japan Sea Side – application of JUICE catalog

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Understanding the thickness of seismogenic layer is important parameter for the earthquake hazard assessment because this relates to the size of earthquakes caused by the active fault. We investigated the indexes D5 and D95 as the upper and lower limits of the seismogenic layer defined as the depth above which 5 % and 95 % of the whole crustal earthquakes occurred from the surface, respectively.

In previous study, we relocated hypocenters for 12 years between 2001 and 2012 from the NIED Hi-net catalog (hereinafter referred as “JUICE catalog", Yano et al. 2016) for high resolution hypocenter locations (Depth ≦40 km, M≧0.0). In order to satisfy Gutenberg-Richter magnitude-frequency relation, we extracted events with magnitude eaqual to or greater than 1.5 from the JUICE catalog. We then estimated the D5 and D95 using the same method as Matsubara and Sato (2015).

The general pattern of our results is consistent with similar studies of D10 and D90 (e.g. Matsubara and Sato, 2015; Tanaka, 2004; Omuralieva et al., 2012). For example, very deep D95 lies beneath the northern Hokkaido and northern Honshu and very shallow D95 extends along the belt-like volcanic areas. Moreover, this study enables to reveal that D5 and D95 have local variability of depth along active faults because we used the JUICE catalog, in which these hypocenters are confined into each cluster of seismicity and some active faults.

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Heat flow map of the Czech Republic, revisited

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The existing heat flow pattern of Central Europe is reasonably well known since the late eighties. However, in recent years additional geothermal data have been accumulated which provided a certain possibility to reconsider the previous knowledge and update it. A revised version of heat flow map of the Czech Republic is presented together with the maps of the isotherms at depths of 500, 2000 and 5000 meters. The geothermal data were thoroughly completed with similar information available from the surrounding countries, the paleoclimatic corrections were applied on the whole dataset. 3D numerical model based on the additional information summarizing the results of the laboratory measurements of the radiogenic heat production and heat conductivity of collected rock samples was proposed to describe the crustal thermal structure of the studied territory and allowed to delineate the potential zones for the utilization of deep geothermal energy. The influence of the convective heat transfer on subsurface temperature field in the discharge and recharge areas, namely in southern and western Bohemia, was briefly discussed in context of regional heat flow density pattern.

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Heat flow and tectono-thermal histories in cratons of China

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There are altogether 1230 heat flow data in the continental area of China, and most of them concentrate in the three cratons: the North China Craton, the Tarim Craton, and the Yangtze Craton. Heat flow in these cratons displays much different characteristic., which is 42.5 mW/m2 in the Tarim Basin, 61 mW/m2 in the western NCC, ˜64 mW/m2 in the eastern NCC, 71.2 mW/m2 in Subei Basin of the Lower Yangtze Craton, and 53.2 mW/m2 in the Sichuan Basin of the upper Yangtze Craton. In general the high heat flow locates at the active continental block (e.g. eastern NCC) and the low heat flow at the stable craton block (e.g. Tarim). Each of the cratons has experienced complicated evolution histories since their formation, presents distinct thermal regime, and displays different stability. The Tarim Craton keeps its stability till now. The eastern North China Craton has been destructed in the Mesozoic, but the western North China Craton still stable. The stability of the Yangtze craton is a controversial issue, and the newest study believed it experienced similar tectono-thermal events as the North China Craton and has also been destructed in the Mesozoic. Several sedimentary basins developed in these cratons, and most of them are rich of oil-gas resources. These basins have different formation mechanism and experienced distinct tectono-thermal evolution, which resulted in individual thermal histories. The sedimentary basins have recorded distinct thermal evolution of these craton. Heat flow data, together with basins' tectono-thermal histories in these cratons may help to provide ideas for geodynamical mechanism on the craton stability/destruction, as well as implications for hydrocarbon generation.

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Indications of “hot belts" along passive continental margin of Brazil

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Analysis of geothermal data for the coastal sedimentary basins of eastern Brazil has revealed the existence of an anomalous high heat flow belt along its passive continental margin. The main characteristics of this anomaly are the geothermal gradients in excess of 30oC/km and heat flow greater than 70mW/m2. It is confined between zones of relatively low to normal heat flow in the adjacent continental regions to the west and stable oceanic regions to the east. The width of the belt is somewhat variable, but most of it falls within the range of 100 to 300 km. It is relatively large in the southern (in the basins of Pelotas, Santos and Campos) and northern (basins of Potiguar and Ceara) parts, when compared with those in the central parts (basins of South Bahia, Sergipe and Alagoas). The characteristics of heat flow anomalies appear to be compatible with those produced by thermal sources at shallow depths in the upper crust. Seismicity within the belt is relatively weak, with focal depths less than 10km for most of the events. Such observations imply that “tectonic bonding" between continental and oceanic segments is relatively weak. Hence, it is proposed that “passive" continental margins like that of Brazil be considered as constituting a type of plate boundary that is aseismic at sub crustal levels, but allows for escape of significant amounts of earth's internal heat at shallow depths.

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The efficiency of Borehole heat exchanger system by regional differences

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Borehole heat exchanger (BHE) is an economically and environmentally friendly technology. Therefore, the BHE is beginning to spread around the world. For design and deployment of the system, it is thus important to evaluate the available subsurface heat energy through thermal response tests and/or numerical simulations and to design appropriate systems (depth and the number of boreholes for heat exchange). Geological structures, groundwater properties, and subsurface temperatures are essential input data for the numerical simulations. The evaluations are roughly separated to two models; wide model and local model.
We demonstrate the wide model at first. We illustrate a new construction method of BHE potential map from regional geological structure and measured subsurface temperature for typical Japanese plains. Our main target areas are central part of Kanto Plain and Obama Plain. Kanto Plain is including of Tokyo metropolitan and Obama Plain is located in the central part of Japan and faces the Sea of Japan. We have conducted measurements of subsurface temperatures 25 stations in central part of Kanto Plain and 4 stations in Obama Plain for the evaluation.
A part of the numerical simulations results shows that BHE efficiency increase 20 % when subsurface temperature rise up 5 degree and the efficiency also increase 30 % when groundwater flow vary from 0 to 15 m/year. We show also the efficiency of BHE difference due to the difference of the subsurface temperatures in the worldwide cities (example for Tokyo, Osaka, Bangkok, and Berlin).
We have also discussed an influence of subsurface warming effect on the BHE efficiency by numerical simulations. We reveal that subsurface warming effect increase BHE efficiency of heating drive (inversely, decrease efficiency of cooling).

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Assessment of efficiency and potential of a ground source heat pump system under geological complexity in Japan

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This paper presents an assessment of the efficiency and the potency of a ground source heat pump system (GSHP) in Japan. This research is fundamental on the 3D geo-database which consists of over forty-thousand water well drilling reports. Indicator kriging interpolation is applied to estimate the soil/rock types in any location. The accuracy of kriging interpolation is validated in the leave-one-out cross validation. The geodatabase translates the probability estimates of soil/rock types to the effective thermal conductivity and transmissivity as matched with the in-situ measurements. The database also provides the groundwater flow simulation results by AIST to evaluate heat advection effects in the Holocene, Pleistocene and Neogene layers. This study performs the GSHP simulation by using the Ground Club, which was developed based on the cylindrical heat source theory to calculate ground temperatures rapidly with accuracy. The Ground Club is also useful to assess the advection effects of groundwater flow in the multi-layered formations. The assumed GSHP is composed of a commercial heat pump and a vertical borehole heat exchanger (BHE) in a standard residence. The total external area of the residence is 313 m2 and the U-values are ranged from 0.46 W/m2/K in the cold region to 0.87 W/m2/K in the warm regions. The heat demands are variable according to the hourly data of the outdoor temperatures and the insolation amounts. In each location, the system efficiency values on a third year are estimated under different cases of assumed BHE lengths, so that minimum lengths of BHEs for the required efficiency are determined. The simulation is demonstrated all over the country with a grid of 0.25 km in space. The results are averaged into a grid of 1 to 10 km in space for a national map. The map contributes to the assessment of the efficiency and the possibility of the GSHP under the regional situations of geology and groundwater in Japan.

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Alternative use of subsurface energy as heat pump or groundwater

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Thermal energy in subsurface environment can be used sustainably if we can manage the resources carefully. Demands for energy to melt snow accumulated on the roads is increasing in many coastal snowy areas in Japan. There are alternative uses of subsurface energy, and the one of them is the use of groundwater for melting snow, because the temperature of the groundwater is relatively higher in winter than that of the air and river water, therefore groundwater itself is a useful heat source to melt snow. Another way is the use of heat pump, which is the use of thermal energy in shallow subsurface for melting snow. In this study, the effects of alternative use of subsurface energy as heat pump or groundwater have been analyzed by three-dimensional groundwater flow model with subsurface thermal analyses in the snowy areas of Obama City, Fukui Prefecture, Japan.

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Subsurface temperature modelling with inverse parameter optimisation

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Focus on the utilization of geothermal energy as a sustainable energy source has resulted in extensive geothermal exploration activities with a demand for procedures for obtaining reliable information on subsurface temperatures and thermal resources. Subsurface thermal information is basically obtained from two different sources: direct observations by measurements in boreholes and indirectly by numerical modelling. We present a modelling methodology which ensures consistency between model temperature predictions and measured temperatures and which provides easily updated models.
Structural and lithological information, data on rock thermal properties and current information on borehole temperatures and heat flow are integrated into a parameterised 3D subsurface model, for which the heat equation is solved by applying combined numerical forward modelling and inverse optimisation methodology. A priori values of model thermal parameters, such as thermal conductivity and heat production, as well as background heat flow may be adjusted, within uncertainty limits, to ensure model agreement between observed borehole temperatures and resulting model estimates. Inverse parameter calibration is carried out by minimising an objective function comprised of a weighted sum of the squared differences between modelled and measured temperatures.
This methodology is applied to Danish and North German sedimentary basins. The resulting thermal models include temperature predictions in a densely spaced 3D grid of subsurface points. Temperature information may be extracted in terms of local temperature-depth profiles, temperature maps for specified geological horizons, such as potential geothermal reservoirs or for selected constant depths. Such models improve our understanding of the subsurface thermal field, including sources of temperature variations and anomalies, and facilitate risk reduction by integration into regional as well as local geothermal exploration.

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Magnetotelluric surveys to delineate shallow reservoir of low-enthalpy geothermal systems in Thailand

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Most of Thailand geothermal fields are classified as the low-enthalpy system which can be efficiently utilized with the current technology for power production. The geothermal exploration assessment program was then initiated. The deep geophysical survey is one of the major parts of the program.

Since 2014, Mahidol University incorporation with a joint venture leading by Thailand Department of Groundwater Resources has been conducting magnetotelluric surveys on the selected geothermal fields in northern and southern Thailand. The 3-D resistivity distribution of those fields, up to a depth of 2 km, were carried out by a 3-D magnetotelluric inversion, WSINV3DMT, using impedance tensor and tipper data.

The obtained resistivity models support the conceptual model of the previously proposed hydrothermal system in most of the fields. The heat source is the deep resistive granitic rocks. The derived model also reveals the geological and fault structures acted as the fluid pathway to the surface where the hot spring manifestation occurred. The shallow conductive structures are mapped and can be referred as the geothermal reservoir in the formed of fluid-filled fractures in weathered granitic rocks or a clay cap formed in the sedimentary layers. The deep 1 km drilled well was then conducted in one of the fields. The core log data coincides with the resistivity model derived from the magnetotelluric survey. The methodology developed during the past surveys can be applied to other low-enthalpy geothermal fields and could help accelerating the geothermal energy utilization in Thailand.

Evaluation of geothermal energy potential for heating/cooling of the Xi'an Jiaotong University new campus in Xixian, Shaanxi, China

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The Xi'an Jiaotong University (XJTU) is an elite research university in China. It has been tasked by the Shaanxi Provincial Government to develop its new campus as a technological innovation hub in western China. Socioeconomically, the XJTU new campus is located in the Xixian District, a transmission zone between Xi'an and Xianyang designated for ecological urbanization development. Geologically, it situates on the top of the Xi'an Depression of the Guanzhong Basin where geothermal resource is abundant and has been utilized for thousands of years. More than 150 geothermal wells mostly of depths between 1000 to 3000 m are currently in production in the Xi'an –Xianyang area. A preliminary energy demand analysis of heating/cooling for the new campus based on space functionalities shows a maximum load of 179 MW during the 4-month winter heating season from mid-November to mid-March, and 189 MW during the 2-month summer cooling time from July to August. This ongoing project is to evaluate the feasibility for geothermal resource to meet the heating/cooling demand. Based on the data available in the literature, a geological model of the Xi'an Depression has been established. Five Cenozoic formations have been identified as geothermal water bearing strata within the depth down to 5 km. Although the new campus occupies an area of about 3.12 square km, we use a reservoir area of 5 square km in our resource assessment because extraction of underground geothermal fluid does not have to be restricted within the campus boundary. Geothermal resource of each reservoir stratum is calculated in terms of formation thickness, porosity, and temperature data. The thermal energy reserve for the XJTU new campus is estimated to be 14900 billion Kcal. In search for an optimal and sustainable geothermal energy application plan, we are in the process of simulating various production schemes. Results will be presented at this conference.

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RINGEN - Research INfrastructure for Geothermal ENergy

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RINGEN (Research INfrastructure for Geothermal ENergy) is a unique research institution – first of its kind in the Czech Republic, whose hosting institution (founder) is Faculty of Science of Charles University in Prague. The RINGEN promotes research and development in the country and offers specific services related to the practical use of geothermal energy. Its key asset is the existence of 2.1 km deep testing geothermal borehole PVGT-LT1 (drilled in 2006-2007) and the basic seismic monitoring network (established in 2014) allowing in-time testing. RINGEN is the Czech contribution to European and global research and development in the area of geothermal energy, which until now has been rather limited to the cooperation of individual national research centers and/or individual researchers without the appropriate material and scientific background. We want to further broaden its scope to focus on induced seismicity, detection capabilities of seismic networks, hydrogeological, geomechanical and geotechnical conditions and on mathematical modeling of underground geothermal exchangers as well as the studies of the geothermal properties of rocks. Among the nearest goals belongs a proposed new 4 – 5 km deep borehole to be drilled at Litomerice area in northern Bohemia. The so far obtained RINGEN results are briefly presented with our desire to open the RINGEN facilities to the international cooperation, research institutions or researchers from anywhere are welcome to establish a partnership.