Dynamic initiation of decollement in accretionary prisms

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The decollement of the Nankai accretionary prism is a shallow dipping thrust that cuts through an unremarkable and homogeneous sedimentary layer. This observation contradicts the intuition that (1) decollements develop at the favor of weaker sedimentary levels; and that (2) thrusts form at about 30 degrees from horizontal (Andersonian theory of faulting).
There are many examples of accretionary prisms and fold and thrust belts where weak sedimentary levels act as decollement (e.g. evaporites in the Jura and Zagros, shale in the Alberta foothills). Prediction of the taper angle using the critical Coulomb wedge theory also suggests that decollements are often weaker than the rocks composing the bulk of the wedge (e.g. Davis, 1983). On the other hand, it is well documented that rheological weakening can be a consequence of fracturing, rather than its cause, e.g. because fractures act as fluid pathways that can change the local lithology and raise the fluid pressure.
In this contribution, we derive an analytical solution for the stress orientation in a compressed region of homogeneous perfectly plastic material near the surface. We show that for a perfectly plastic rheology the stress orientation is a function of the push direction, the intensity of the push, the surface topography and material properties. All those parameters collapse into a dimensionless number.
Since we consider homogeneous material properties, it is less suited to analyze present day accretionary prism than the critical taper theory. However, it is particularly suited to study the initiation of decollement, before fault-induced weakening takes place. Our analytical solution (1) is general for any surface topography described by a function differentiable in x; (2) predicts generally non-planar decollement; and (3) does not make use of small angle approximation, even for the case of cohesive plasticity.
The analytical solution is tested against a series of static (<<1% shortening) numerical models including visco-elasto-plastic rheology.

Keywords: decollement, accretionary prism

Crustal anisotropy of Cascadia subduction zone revealed by ambient noise tomography

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We construct 3D crustal shear wave velocity models for the Gorda-Juan de Fuca region using ambient seismic noises. Continuous data from Cascadia Initiative Community Experiment - OBS component were used. In our wavelet-based multi-scale inversion technique, both the isotropic and anisotropic components are taken into account. Previous studies of shear-wave splitting (SWS) with SKS and SKKS using OBSs pointed out that fast directions in this region rotate increasingly towards the absolute plate motion direction with increasing distance from the mid-ocean ridge. However, our preliminary result of 2D phase velocities for Rayleigh waves show a trench-parallel fast direction at periods 2 −25 s, i.e., the crustal and shallow upper mantle anisotropy differs from the results of SWS studies. This disparity between our result and the plate motion-parallel fast direction from the earlier studies implies that there might be a two-layer structure with different deformation fabrics in this region. We will integrate our models with the 3D models from body wave tomography and seismic anisotropy from SWS, and discuss their tectonic implications.

Keywords: Crustal anisotropy, Ambient noise tomography, Cascadia subduction zone

Recent crustal movements and deformations of the southeast of Russia as seen from continuous GNSS measurements

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The Far East geodynamic GNSS network was established in 2009-2010. It covers the southeast of Siberia and Sakhalin Island and consists of more than 15 continuously operating GPS/GLONASS stations. Its data along with observations stemming from IGS and other available GNSS networks were used to estimate the crustal velocity and deformation field of the investigated region before and after March 11, 2011 when the Great 2011 Tohoku earthquake struck the Pacific coast of northern Honshu, Japan and caused measurable coseismic displacements through Northeast Asia. The BERNESE 5.2 software was used for GNSS data processing. The ITRF2008 and ITRF2014 reference frames were adopted for data analysis. The calculated interseismic GNSS velocities indicate relative internal (between network sites) and external (with respect to the Eurasian tectonic plate) stability of continental part of the investigated region. The velocity boundary between Sakhalin Island and continent was discovered which possibly tells on their relation to different tectonic plates/microplates. The intense postseismic crustal displacements caused by the Great 2011 Tohoku earthquake have also been observing in the Russian southeast near the triple junction of Russia, China and North Korea national boundaries. The maximum observed cumulative postseismic displacements have already exceeded 70-80 mm (the corresponding coseismic shift is equal to ~50 mm). Afterslip or viscoelastic rebound models separately cannot reproduce properly all parts of the observed GNSS site position time series, however, viscoelastic approximation is working well on the time interval of 0.5-3 yrs after the mainshock. Two-layers viscoelastic model with Maxwell's viscosity of about $5\cdot 10^{18}$ Pa·s adequately fits horizontal components of the observed postseismic displacements but fail to explain vertical component. The 2013 Okhotsk deep focus earthquake generated measurable coseismic displacements which were detected by Kamchatka and our GNSS network. The annual velocities of GNSS sites located in the northern part of Sakhalin Island demonstrate notable change after the mainshock of the Okhotsk deep earthquake which, probably, could be explained by the existence of notable postseismic mantle response.

Keywords: crustal displacements and deformations, GNSS observations, secuar and postseismic motion modeling

Crustal anisotropy and deformation of the Tibetan Plateau based on the Pms of the receiver functions

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As the frontier of the plateau uplift and extension, the northeastern margin of the Tibetan Plateau (NE Tibetan Plateau) is an ideal place to study the crustal and upper mantle deformation characteristics and coupling relationship of the Tibetan Plateau. However, the resolution and reliability of previous studies in this region are suffered from insufficient observations. In this paper, with an array of 675 dense seismic stations in the NE Tibetan Plateau, we obtained the crustal anisotropy parameters by using the Pms phase in receiver functions. The results show that the average splitting time of Pms wave is approximately 0.5 s, which is mainly caused by the middle and lower crust. In the Tibetan Plateau, the fast polarization directions of Pms are mainly NW-SE, which are parallel to the directions of SKS and the maximum shear strain directions. In the outside of the plateau, such as Alxa block and western Ordos block, the fast polarization directions of Pms are NE-SW, which have large intersection angles with the directions of SKS. We infer that the deformation of the crust and upper mantle in the Tibetan Plateau is coupled and is controlled by simple shear deformation with the direction of NW-SE, while the crust-mantle deformation in the outside of the plateau is decoupled, and the crustal deformation is mainly caused by the differential movement of the middle and lower crust with the direction of NE-SW. The observations show an interesting finding that the Alxa block and Ordos block, which are always considered to be the stable blocks, may be experiencing crustal deformations at this stage.

Keywords: Tibetan Plateau, crustal deformation, anisotropy, receiver functions

The Study of Nowadays 3D Crustal Movement in Fenwei Graban System

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Fenwei rift zone located in the east and south of the Ordos block is still active in China mainland, and it is tectonic boundary separating the Ordos block, Qinling tectonic belt and north China block. Due to the limited observation technique, the current tectonic movement and deformation of Fenwei rift zone are still not very clear and the formation mechanism of the Fenwei rift zone has no consensus. GPS data observed from 2009 to 2014 were collected at 527 campaign–mode and 32 continuously operating GPS stations are processed and get a precise and high spatial resolution horizontal velocity field and strain field. The results reveal that the belt between Shanxi basin and western mountains is under extension with strain rate of 0.01-0.03 ppm/a. Meanwhile the belt between Shanxi basin and eastern mountains is under contraction with strain rate of 0.02-0.03 ppm/a. The western boundary faults of Shanxi basin such as Loyunshan fault, Jiaocheng Fault et al. have 2-3 mm/a of left-lateral slip and 2-3 mm/a of normal-fault extension. But the eastern boundary faults of the basin such as Taigu fault have 1-2 mm/a of right-lateral slip and 1-3 mm/a of normal-fault contraction. There is 2.1 mm/a of shortening motion in southwest of Ordos Block as well as the velocity gradually changes near Lupanshan fault system. It reveals that the fault system is locked in deeper. Weihe fault system show left-lateral slip of 1.0 mm/a and weak extension deformation.
The present crustal vertical velocity field image relative to ITRF2008 is obtained by the precise leveling data from 1970 to 2014 and the vertical velocity of the continuous GPS stations within this region were as a priori constraints. The image reveal that the Ordos block shows overall uplift rates of 3mm/a and Liupanshan-longxi block shows uplift rates of 4-5mm/a. Weihe basin shows subsidence rates of 3-5mm/a relatively Ordos block, while subsidence rates of 2-4mm/a relatively the North Qinling Mountains. Relatively Ordos block and Zhongtiaoshan , the Linfen - Yuncheng Basin demonstrate a subsidence rates of 4-5mm/a. Using the block model and dislocation model, the slip rates and locking depths of the major faults in the Fenwei rift zone were obtained. Our research results provide an important basis for the study on the interaction mechanism between the Qinhai-Tibet block and north China block and long-term risk prediction of regional large earthquakes.
In our study, we suggest a flow model by combing the results of FEA, analysis of Crustal movement profiles with lithospheric mantle deformation from the SKS fast-wave direction. The soft materials beneath the upper crust of Tibet plateau flow towards NE direction, because of the obstruction from the deep root of the Ordos block, the west part flow to Yinchuan along the edge channel, and the south part flow towards the North China across channel under the Fenwei graben.

Keywords: Fenwei gruban, Crustal movement, Block model

2012 Indian Ocean Coseismic Model: Joint Evaluation in 3-D Heterogeneous Earth Structure Inferred from GPS and Tsunami Data

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Determination of conjugate fault orientation in a complex oceanic intraplate earthquake is remaining challenging. Lack of observation network around the fault source region and extremely rare event give the estimation of fault structures become debatable. On April 2012, Mw 8.6 earthquake struck off the west coast of northern Sumatra about 300 km west of the Sunda trench. The 2012 Indian Ocean Earthquake, which is the largest intraplate earthquake in the history of instrumentally recorded events, has been reported to have a complex conjugate fault ruptured within multiple fault segments. The complex conjugate fault has been found to be NNE trending left-lateral fracture zones as the main features (Wei et al. 2013, Satriano et al. 2012) while other found to be WNW trending right-lateral faults structure had greater slip (Yue et al. 2012, Hill et al. 2015). Here, we propose a joint evaluation based on Global Navigation Satellite System (GNSS), ocean bottom pressure sensors, and tsunami waveform recorded at tide gauges by assuming heterogeneous earth structure to resolve the fault orientation. In this study, we develop three-dimensional heterogeneous earth models including subducting slab, 3-D earth velocity structure, topography and bathymetry as well as spherical earth using 3-D Finite Element Method (FEM) to evaluate previous coseismic model. In order to obtain the actual slip distribution within our model, we adjust slip distribution using slip scaling. We conduct iterative model-observation best fit calculation of reduced chi-squared until reach minimum misfit. Furthermore, we propose chi-squared misfit based on slip scaling as another consideration to evaluate the coseismic model.

Keywords: Coseismic, FEM, GNSS, Tsunami

Coseismic deformation and tectonic implications of the 2016 M6.6 Meinong earthquake, Taiwan

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A M6.6 earthquake occurs at Meinong, Taiwan at 03:57:27 on February 6, 2016 local time (UTC+8). This earthquake caused severe damage and 117 deaths around several towns of Tainan City. We estimate coseismic displacements from continuous GPS and InSAR images. We process GPS daily solutions and calculate coseismic displacements from the differences between average positions for seven days before the earthquake and average positions for four days after the earthquake. The maximum horizontal displacement is about 5 cm and maximum vertical displacement is about 9 cm from GPS. We conduct dislocation models to estimate fault slip and fault geometry and the results show that the main slip area is at depths of 10-20 km and the orientation of the fault plane is E-W dipping to the north. In addition, we process ALOS2 images and the results show a region of deformation 10 km west of the hypocenter. The deformation region shown in InSAR results indicates deformation in mudstone at shallow depths, which is different from the dislocation model. This shallow deformation pattern is consistent with preseismic deformation pattern constrained from PS-InSAR and leveling. The shallow deformation might be controlled by local stress condition in the mudstone area.

Keywords: Coseismic deformation, InSAR, GPS

Characteristics of postseismic deformation associated with the 2016 Meinong earthquake

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The M_L=6.6 Meinong earthquake on February 6, 2016, which caused 117 deaths and severe damage in southern Taiwan, is the most destructive seismic event in the recent decade. The epicenter is in Meinong but major coseismic deformation occurred in Guanmiao and Longqi, about 10 km to the west of the epicenter. In addition to the seismogenic fault at ~15 depth, there may be a triggered fault at shallower depth based on an inversion of InSAR and GPS observations. Therefore, it is important to examine if the postseismic deformation continues being triggered by two faults like the coseismic deformation and if the location of postseismic deformation is around the coseismic slip area.
We use InSAR and GPS to identify the distributions of postseismic deformation of the Meinong earthquake, and then infer the location and magnitude of the afterslip, which will be helpful for us to better understand the characteristics of surface deformation and the active tectonics of the area.

Keywords: Meinong earthquake, postseismic deformation, InSAR, GPS

Surface Creep Analysis of the Fengshan Fault in SW Taiwan from GPS observations and PSInSAR

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Previous studies based on GPS observations have found that the Fengshan fault may be a major active structure with surface creep in southwestern Taiwan. However there was no historic earthquake along this fault and no solid geologic evidence to confirm whether the fault exists. Therefore, the geometry and activity of the Fengshan fault remain unclear. Whether the fault acts like stick-slip or creeping will make great impacts on the national constructions and public properties. Thus, it is necessary to evaluate the potential activities of the Fengshan fault.

We use 56 continuous GPS stations and 167 campaign mode GPS stations in the study area for the horizontal displacements and also 483 leveling points for vertical displacements. In addition, we use ascending data of the ALOS image with PS-InSAR techniques to analysis the Fengshan fault. We remove vertical signals from the line-of-sight (LOS) velocities based on leveling data. The fault parallel component has about 14.3 mm/yr differences across the fault at the northern, 12.6 mm/yr differences across the fault at the middle segment and 17.4 mm/yr differences across the fault at the southern segment, and the fault normal component has 3.5 mm/yr, 2.6 mm/yr and 3.6 mm/yr differences extension components across the each segments.

The Fengshan fault is a left-lateral strike-slip fault in about 15 mm/yr and lengthening of about 3 mm/yr. This fault is creeping in the middle and southern segments. The northern segment of the fault is probably locked in about 1.5 km width. The locations of mud volcanos in the Niaosong, Kaoshung and the Wandan, Pingtung, are consistent with the fault trace of the Fengshan fault well and are proposed as the geological evidence of this fault.

Keywords: GPS, PSInSAR, Fengshan fault, Velocity profile, Creeping fault, Locked fault

Crustal deformation of earthquakes that occurred in Italy on 2016 detected by ALOS-2/PALSAR-2

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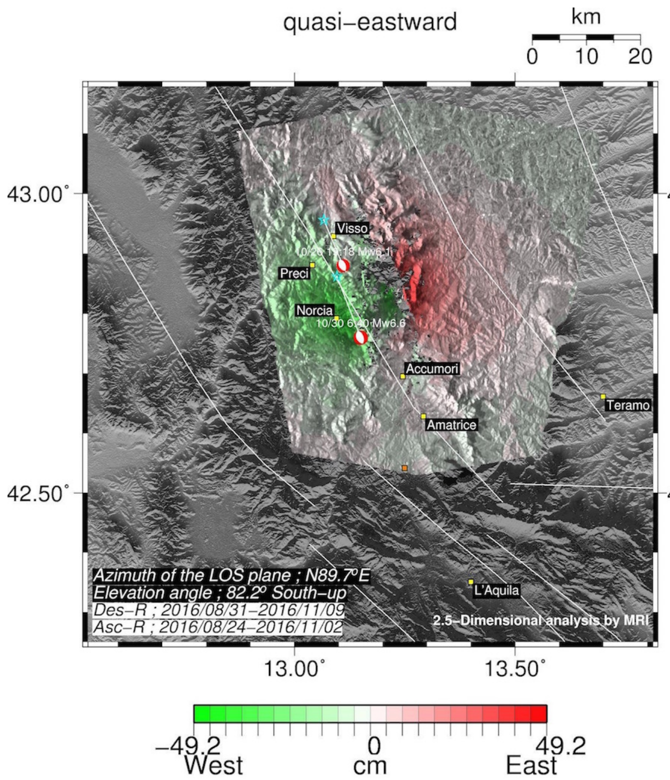
Three earthquakes of magnitude 6 classes occurred in the central of Italy on 2016 (August 24: Mw 6.2, Depth of 4.4 km - 10 km SE of Norcia; October 26: Mw 6.1, Depth of 10 km - 3 km NNW of Visso; October 30: Mw 6.6, Depth 8 km - 7 km N of Norcia). In any of the earthquakes, a lot of buildings collapsed near the each of epicenter, causing great damage. In addition, in the vicinity of this epicenter, there was a case where an earthquake of M 6.0 or more occurred in the past. In recently, the moment magnitudes 6.0 earthquake occurred mainly at L'aquila in April 2009 located in the 10-15 kilometers south of the current earthquake. This earthquake caused severe damage that over 295 dead and more than 1,000 injured.
In Italy, very complicated and many active fault are reported by Istituto Nazionale Geofisica e Vulcanologia (INGV). The reason is that the African plate and the Eurasian plate collide with each other, and the area is pushing each other, and it is complex both tectonically and geologically. Especially, in the Apennine Mountains where these earthquake occurred, it is the place where the earthquake occurs due to the forces to the east and the west of the province. As evidence by this fact, the result of the source process analysis shows a normal fault.
ALOS-2, was launched on May 24, 2014, has an L-band SAR (PALSAR-2) and survey all over the world. We calculated the crustal deformation by differential interferometry analysis on three earthquakes occurred in Italy. In addition, we compared with the slip distribution acquired by the source process of JMA and tried to estimate the fault plane. The earthquake that occurred on October 26 and 30 detected the westward displacement near the epicenter and the west side and detected the eastward displacement on the east side of the epicenter. In addition, subsidence components were detected near the epicenter. Therefore, we judged that the mechanism of these earthquakes is a normal fault of W-dip.
Some of PALSAR-2 data were prepared by the Japan Aerospace Exploration Agency (JAXA) via Geospatial Information Authority of Japan (GSI) as part of the project ‘ALOS-2 Domestic Demonstration on Disaster Management Application’ of the SAR analysis of earthquake Working Group. Also, we used some of PALSAR-2 data that are shared within PALSAR Interferometry Consortium to Study our Evolving Land surface (PIXEL). PALSAR-2 data belongs to JAXA. We would like to thank Dr. Ozawa (NIED) for the use of his RINC software. In the process of the InSAR, we used Digital Ellipsoidal Height Model (DEHM) based on the Shuttle Radar Topography Mission (SRTM 4.1) provided by Consortium for Spatial Information (CSI) of the Consultative Group for International Agricultural Research (CGIAR), and Generic Mapping Tools (P.Wessel and W.H.F.Smith, 1999) to prepare illustrations.

Keywords: ALOS-2/PALSAR-2, InSAR, Crustal deformation, Italy Earthquakes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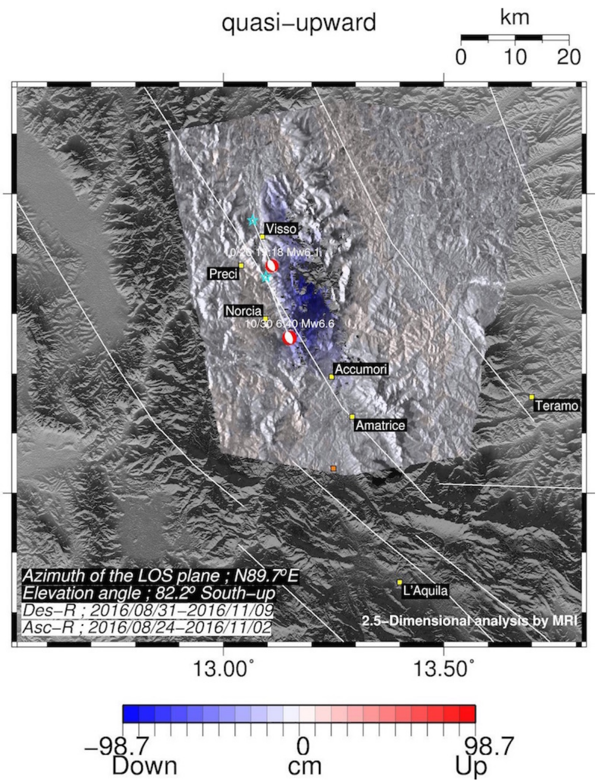
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Time dependent block fault modeling of Japan

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Abstract
We developed a time dependent block fault modeling program and applied it to the GNSS data in Japan. The results based on the data before the 2011 Tohoku earthquake shows afterslips of the 2003 Tokachi-oki earthquake, weakening and restoration of coupling off Miyagi area afther the 2005 Miyagi-oki earthquake, weakening of coupling off Ibaraki and Fukushima after the 2008 off Ibaraki and Fukushima earthquakes, which continued just before the 2011 Tohoku earthquake. The analysis of the GNSS data after the 2011 Tohoku earthquake shows Bungo slow slips, east coast Kyushu slow slips, Kii channel slow slips.

Introduction

It is very important to estimate interplate coupling in subduction zones to assess the source region and magnitudes of the expected subduction earthquakes in Japan. In particular, the probabilities of the anticipated Tokai and Nankai earthquakes are estimated to be high within 30 years period. Under this circumstance, many studies to estimate interplate coupling were conducted. However, those studies did not take into consideration temporal changes. In this study, we developed a time dependent block fault modeling program and applied it to the nationwide GNSS data.

Analytical Method

Hashimoto et al. (2000) conducted a block fault modeling of Japan based on GNSS data. We used the geometry of the block fault model of Japan adopted by Hashimoto et al. (2000). In inland area, we modeled boundaries of the microplates of Japan by rectangular faults and used parametric spline surfaces in subduction zones along the Japan trench, Sagami trough, and Suruga and Nankai troughs. Base on the adopted block fault model of Japan, we estimated interplate coupling on the plate interface by employing the time dependent inversion program which was developed by this study. We used east-west, north-south, and up-down position time series of GNSS data at approximately 1200 GNSS sites in Japan for the periods between 1997-2011 before the 2011 Tohoku earthquake and between 2013-2015 after the Tohoku earthquake.

Results and discussion

The result shows afterslip of the 2003 Tokachi-oki earthquake (M_w8.0) on the plate interface between the Pacific plate and the continental plate. The afterslip was observed in source regions of the 2003 Tokachi-oki earthquake and the afterslip area moved to northeast over time. The weakening and restoration of interplate coupling after the 2005 Miyagi earthquake (M_w6.8) was observed for the period between 2005 and 2007. Weakening of the coupling off Ibaraki and Fukushima was observed after the 2008 Fukushima (M_w7.0) and Ibaraki earthquakes (M_w6.9). This weakening continued just before the 2011 Tohoku earthquake. With regard to the Philippine Sea plate, our result shows Bungo slow slip in 1997, 2003, and 2010 in the Bungo channel area between Shikoku and Kyushu Islands. In addition, interplate coupling was weakened in 2002 and 2005 in the Pacific coastal area of Kyushu Island, indicating slow slips in this region. For the data set after the Tohoku earthquake, we detected the Bungo slow slip in 2013 and 2016, and the Pacific coastal area slow slips of Kyushu Island, and Kii channel slow slip. These result were derived without detrending of position time series, suggesting the effectiveness of the developed time dependent block fault modeling.

Keywords: block fault modelong, interplate coupling, slow slip

Cluster Analysis of the GNSS Velocity Field in the Tohoku Area, northeasten Japan

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Recently, the cluster analysis technique has been applied to GNSS velocity data by Simpson et al. (2012) to reveal tectonic boundaries around the western USA. Assuming a number of clusters, the technique classifies GNSS velocities into some clusters, which shows similar characteristics. The optimal number of clusters can be determined by a statistical test (e.g. the gap statistic by Tibshirani et al., 2001). The advantage of this technique is to extract block-like behavior and to identify tectonic boundaries without considering geological and/or geographical informations. Loveless and Meade (2010) constructed a model composed of 20 blocks in Japan (JB1 model). This model in Tohoku area has two block boundaries, one along the Ou backbone range and the other along the eastern margin of the Japan Sea. The purpose of this research is to apply this clustering technique to the GNSS velocity field of the Tohoku Area, and compare with the JB1 model and the known fault system. GNSS data obtained from 298 continuous GNSS stations operated by the Geospatial Information Authority of Japan and Tohoku University are analyzed using the precise point positioning strategy of the GIPSY/OASIS-II software. We obtain the site velocities by fitting a linear function into coordinate time series from 1 January 2010 to 8 March 2011. We performed the cluster analysis for the horizontal components of the GNSS velocity field with the k-means clustering method. First, assuming the number of clusters we label every site with a cluster randomly. Then, we calculate the centroids of each cluster, and relabel each site with the closest centroid. This procedure is repeated until no more relabeling occurs. This method, however, has a disadvantage, namely the result sometimes depends on the initial random labeling. To avoid this problem, we carry out a thousand of clustering, and calculate the sum of L2 norm of every site pair in each cluster. Then the case of minimum sum is adopted as the optimal clustering. There is ambiguity in assuming the number of clusters. We decide the optimal cluster number by the gap statistic, which compares an ensemble mean of the logarithm of the sum of the L2 norm calculated from a random data, and the logarithm of the L2 norm calculated from the observed data. The gap statistic usually increases with the number of clusters and become stable around the optimal cluster number. The optimal number is 2 for our data set. The result demonstrates a cluster boundary, which runs along the Ou backbone range, and roughly coincides with the boundary of the JB1 model. There are two regions where our clustering result mismatches the boundary in the JB1 model. The reasons may be the ambiguity in the clustering method and/or the possible failure in estimating the site velocities.

Spatiotemporal interplate locking and aseismic slip distributions estimated by tectonic crustal deformation prior to the 2011 Tohoku-Oki earthquake

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We obtained the horizontal and vertical tectonic crustal deformation in the Tohoku district, by analyzing time series of the GEONET data. We investigated GEONET data for seven years just prior to the 2011 Tohoku-Oki earthquake (M9.0). We set the average displacement rate of three GNSS stations, namely, Murakami, Kurokawa, and Shibata 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 four large earthquakes: the 2003 Tokachi-Oki (M8.0), the 2004 Kushiro-Oki (M7.1), 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 calculated by using all the used GNSS stations and the annual and semi-annual periodic signals from the time series. During the analyzed period, the westward horizontal displacement rates of approximately 2 cm/year were identified in Iwate and Miyagi prefecture on the Pacific Ocean side. We also found that the westward horizontal displacement rates became gradually smaller in Fukushima prefecture on the Pacific Ocean side during the period from 2008.0 to 2011.0 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). Optimal values of the hyper-parameters were determined objectively and uniquely, using ABIC minimization method (Akaike, 1980). The results of our inversion analyses revealed locking of approximately 10 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.

Keywords: GNSS, plate 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.

Keywords: Slow Slip Event, Tohoku-Oki earthquake, Ocean Bottom Pressure Data

Detection of short-term slow slip events along the Nankai Trough

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In the Nankai Trough, slow earthquakes such as short-term slow slip events (SSEs) and long-term SSEs have been observed. Nishimura et al. (2013, JGR) detected short-term SSEs along the Nankai Trough using GNSS data. Kobayashi and Kimura (2016, SSJ fall meeting) tried to detect objectively long-term SSEs along the Nankai Trough using GNSS data. Here, we try to detect short-term SSEs objectively using the method of Kobayashi and Kimura (2016).
We used the daily coordinates of the GEONET F3 analysis operated by the Geospatial Information Authority of Japan. We removed coseismic offsets, artificial offsets, and long-term trend component using 365 day moving median. For the stations in the Chugoku region where the influence of short-term SSEs is not observed, the median within the region was obtained for each day. The median was subtracted from the coordinate value of each station. The S55E (opposite to N55W) component was calculated from the horizontal components. We set points at 0.1 degree intervals longitudinally along the Nankai Trough on the 30-km plate depth contour. For each point, an average value within a rectangular range of 50 ×100 km centered on the point was calculated. Then, we obtained cross correlations with a ramp function with arbitrary gradient period and created a distribution of spatiotemporal correlation values.
We can see many cases that activity of the nonvolcanic deep low frequency earthquakes matches the derived spatiotemporal high correlation values. It seems unsteady displacements which is less than 1 cm in the horizontal vector in that period but are gathered collectively in the region, suggesting the existence of some slip phenomena at the plate boundary. On the other hand, there are also high correlation periods irrelevant to the low frequency earthquakes. We need to adjust so that optimum detection can be performed by changing the slope period, the effective correlation coefficients, the amount of change, the size of the rectangular range, and other parameters.

Keywords: slow slip events, Nankai Trough, GNSS

Development of crustal block motion model, including elastic plate coupling based on MCMC method.

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Introduction

Large earthquakes have been occurred along plate interface due to the subducting oceanic plate. It is necessary to consider the relative plate motion for evaluation of earthquake potential. Hashimoto and Jackson (1993) defined the small plates as crustal blocks and estimated the crustal block motion in and around Japanese islands using the trilateration and triangulation data. Owing to the introducing of inland GNSS observation(GEONET), inland relative block motion has been clarified more accurately. And then, it was estimated that spatial interplate coupling distribution along crustal block boundary, such as the plate convergence zone, too. In addition, development of seafloor geodetic observation technology will reveal crustal deformation near the trench. In order to more accurately estimation of coupling along plate interface, it is necessary to consider the interaction between crustal block motion and coupling at simultaneously. In this study, we developed a new crustal block motion model to estimate the crustal relative block motion with the interplate coupling effect.

Previous crustal block motion analysis

In many previous studies, DEF-NODE (McCaffrey., 1995) can analyze the crustal block motion. It employed rectangular plane faults along crustal block boundary. It estimates the crustal block motion, internal strain of block, and the coupling along crustal block boundary based on nonlinear estimation (e.g., Wallace et al., 2005).
Loveless and Maede (2010), on the other hand, divided in and around Japanese islands into 20 crustal blocks, and estimated the plate motion, slip vectors on the crustal block boundary, and coupling along plate interface, using inland GNSS observation data, based on least squares estimation. However, these methods cannot obtain the covariance of the estimated unknown parameters.

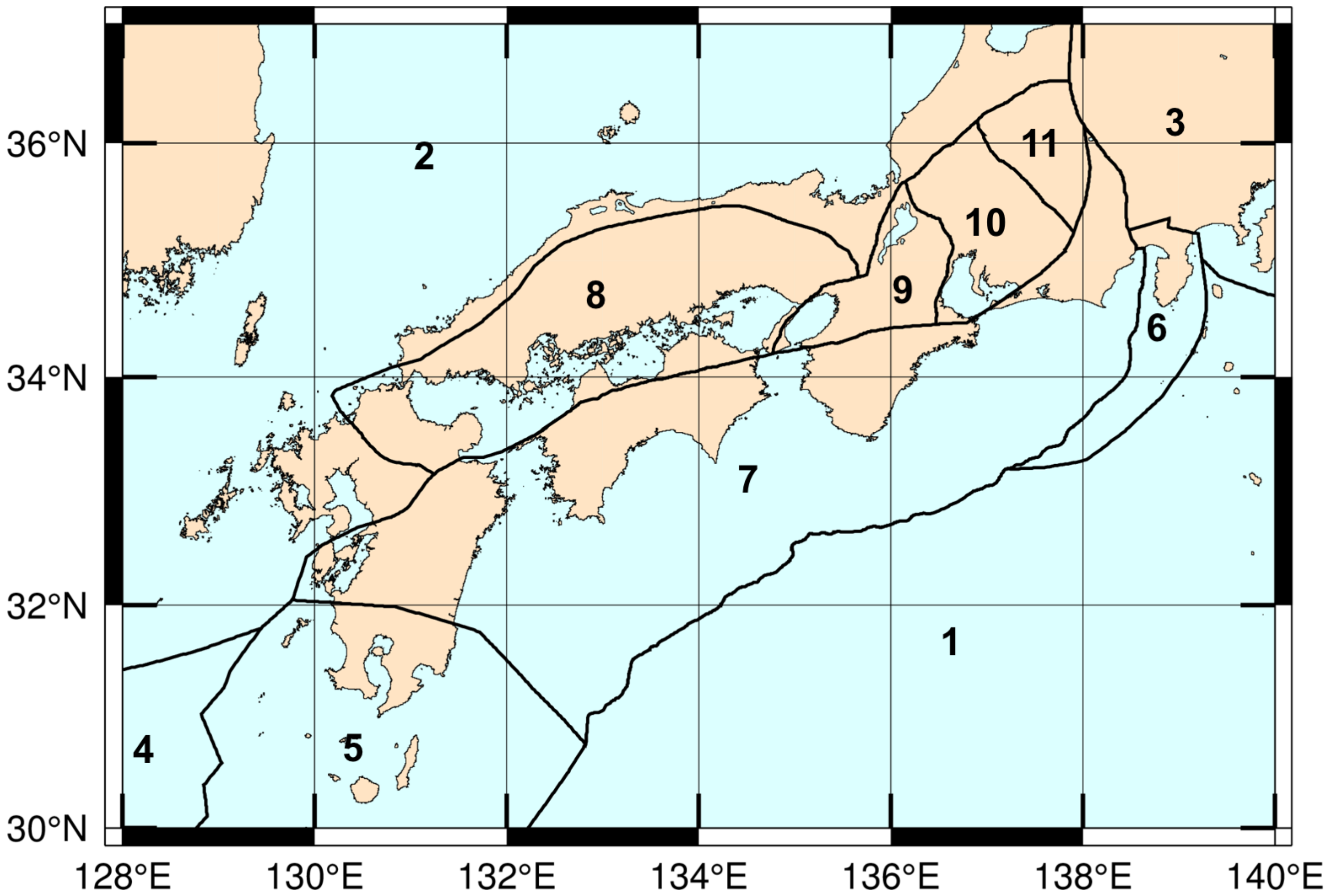
Crustal block motion analysis in this study

The relative block motion(Bv_{ij}) along the two crustal blocks boundary (Br_{ij}) can be described as $Bv_{ij} = Br_{ij} \times (\omega_i - \omega_j)$ using the Euler poles(ω) of the two crustal blocks. Since the interaction between the crustal blocks, we set triangular faults along the block boundary based on a back slip model. First, the slip deficit (χ_{ij}) between the two crustal blocks can be expressed as $\chi_{ij} = C_{ij} Bv_{ij}$ (C_{ij}: coupling coefficient). The elastic response(ve) can be expressed as $ve = G\chi$ (G: elastic response function). The coupling coefficient is a magnitude of slip deficit normalized by crustal relative block motion. Observed crustal deformation(d) is the result of elastic response due to coupling between the crustal blocks and the crustal block motion. It is expressed by $d = ve + Bv = G\, C_{ij}\, (Br_{ij} \times (\omega_i - \omega_j)) + r \times \omega$, meaning that nonlinear equation. Then, crustal block model is constructed by combining these equations, considering the relationship between crustal blocks.
In this study, the coupling between the crustal blocks is estimated using the Markov Chain Monte Carlo method (MCMC). MCMC can evaluate the covariance between estimation parameters. This advantage is possible to evaluate the correlation between the slip deficit at the deep plate boundary and the crustal block motion at inland.
We make new source code for this problem. In this program, it is easy to set up configurations. Thus, it is possible to trial and error with various models. Furthermore, we will implement the elastic response

function derived from finite element method(FEM).
We make a crustal block motion model that is consist of 11 blocks in southwest Japan (see figure). This model consider to plate interface shape and relationship to each blocks.

Future plans
We will use this model to estimate the interplate coupling throughout Japan. As a further step, we will compute spatial coupling distribution on plate interface using FEM.

Keywords: Crustal block motion model, Block relative motion, interplate coupling, Markov Chain Monte Carlo method, GNSS



Fluctuation of the coupling rate along the transient zone in the Shikoku region

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In the southwestern part of Japan, interplate coupling due to the interaction between the subducting Philippine Sea plate and the overriding continental plate causes strain accumulation along the Suruga-Nankai trough. Because slow slip events (SSE) along the subduction zone such as in the Tokai region or in the Bungo Channel region release some of the accumulated strain, the spatiotemporal changes of the interplate coupling and SSE distribution are the direct information for the great earthquake in future. In the Shikoku region, the western part of the Suruga-Nankai trough, Ochi (2015, EPSL) showed a contrast in the strain accumulation process between the eastern and the western part of the region: the almost complete coupling consistently exists beneath the eastern part, while the accumulated strain was released at most about 30% by the repeating SSEs every several years in the western part, or in the Bungo Channel region. This result shows the Bungo Channel region also has a potential for being the rupture area in the future earthquake. Based on the work, we estimate the strain accumulation process along the belt-like transient zone to infer the lower limit of the rupture area. Using the daily coordinates of GNSS Earth Observation Network System (GEONET) in the southwestern part of Japan, the coupling rates along the zone is about 3 cm/yr with an fluctuation of 2-3 cm/yr in some part of the zone. An error of the estimated coupling rate is about 1 cm for the comparable spatial resolution of the GEONET site distribution (~20 km), this fluctuation can be treated as a significant change. We have already discussed the fluctuation only around the Bungo Channel region and the correlation with low frequency tremors (Ochi and Takeda, 2015, JpGU), and we will conduct the same discussion for the whole transient zone.

Keywords: SSE, interplate coupling, southwestern Japan

Horizontal Crusatl Strain in Southwest Japan:Attempt to extract local deformation using a Kriging method

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Crustal deformation field in southwest Japan arc is dominated by the subduction of the Philippine Sea plate (PHS). Strong coupling on the Nankai Trough plate boundary during the interseismic period has caused crustal shortening of the overriding southwest Japan in the direction of plate convergence. At the same oblique subduction of PHS against the strike of the plate boundary has formed a mobile forearc sliver moving along an inland strike-slip block boundary. The Median Tectonic Line (MTL) is the longest strike-slip fault that divides the Nankai forearc sliver from the rest of the southwest Japan arc. Moreover many active faults have been formed within the overriding plate especially in central Kyushu and Kinki districts. Thus interseismic deformation field of southwest Japan consists of "regional elastic deformation and block motion " and "local disturbance affected by active faults and geological structure". In this study we calculate horizontal crustal strain rates from displacement data to better quantify and distinguish regional and local deformations. We use a Kriging method (Mase and Takeda, 2001) known as the spatial optimal interpolation method to extract local deformation. Also we analyze strain field using a spatial smoothing processing by Shen et al. (1996) for comparison. In the latter several different values (15-35 km) are applied for the distance decay constant.

We use horizontal displacement rates derived from GEONET final coordinate time series at 569 sites from Kyushu to Kinki districts during the period of 2006-2009. Regardless of the strain analysis method, the southern part of Shikoku region has been shortened at a rate of 0.15-0.30 ppm/yr in the NW-SE direction due to the PHS convergence. The direction of the compression axis rotates counterclockwise from western Shikoku to southern Kyushu, which implies PHS convergence becomes less effective. Similarly strain rates decrease rapidly with increasing distance from the Nankai Trough. Comparing strain rate fields from two different methods, the Kriging is more sensitive to a local disturbance. However, systematic local deformation affected by active faults and geological structure are not clear though we have expected it around MTL and other tectonic lines. Spatial resolution of original GEONET data may be insufficient to extract local disturbance since its average station separation is 15-20 km. In this sense dense campaign measurements for a specific target will play an important role when it is linked to GEONET.

Keywords: Crustal deformation, Southwest Japan, Strain, Local deformation, Kriging method, GPS

Crustal deformation and a fault model of the 2016 central Tottori prefecture earthquake

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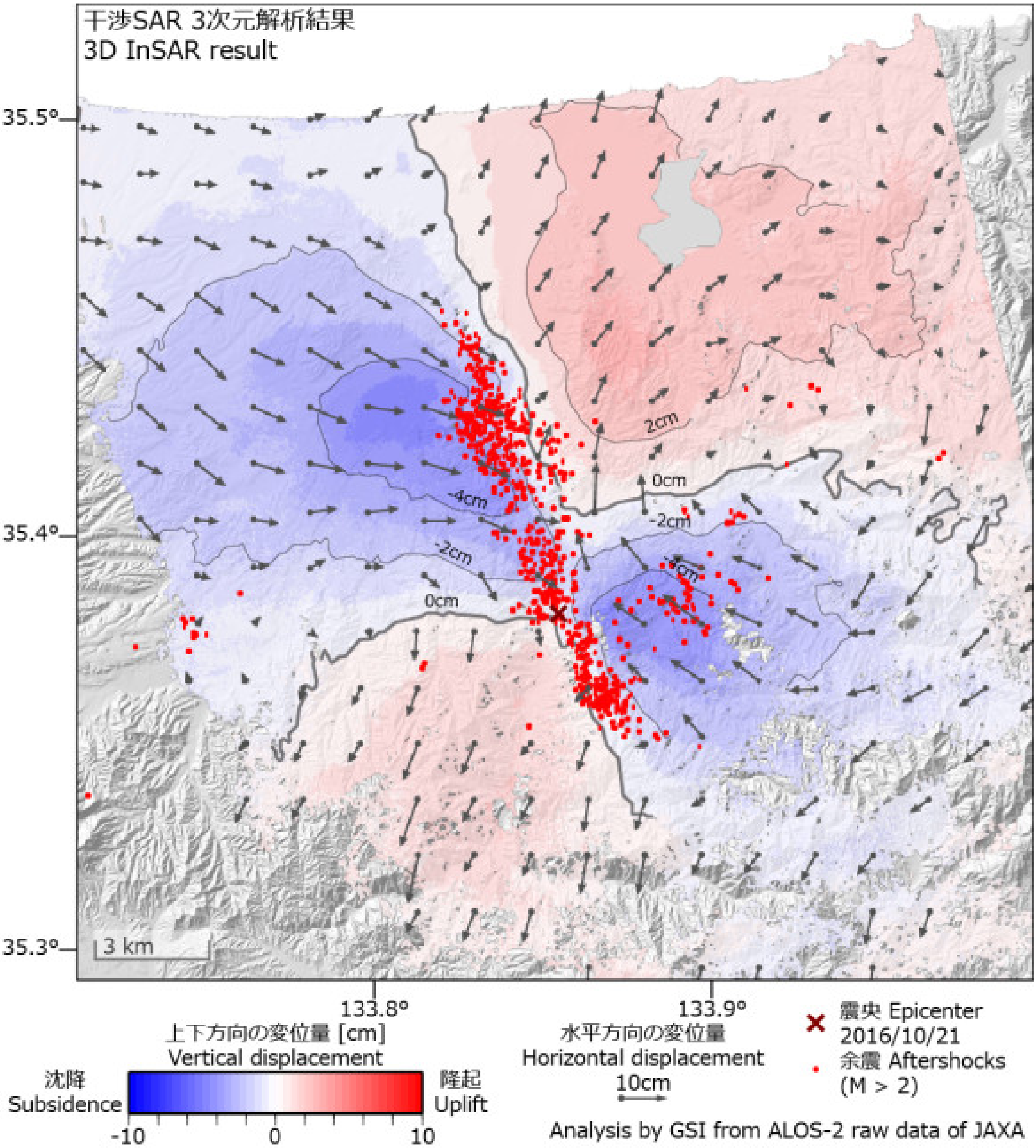
The Mj 6.6 inland earthquake occured on Oct. 21th, 2016 in the central Tottori prefecture, western Japan. Coseismic deformation derived from the earthquake was observed by GNSS and ALOS-2/PALSAR-2 interferometric SAR.
Continuous GNSS observation network (GEONET) is deployed in all over Japan with an 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 10^{18} Nm (*Mw*6.21) from the slip distribution model.

Acknowledgements.
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.

Keywords: InSAR, GNSS, the central Tottori prefecture earthquake


干渉SAR 3次元解析結果
3D InSAR result
35.5°
35.4°
35.3°
3 km
2cm
0cm
-2cm
-4cm
-2cm
0cm
133.8°
133.9°
上下方向の変位量 [cm]
Vertical displacement
沈降
Subsidence
隆起
Uplift
-10
0
10
水平方向の変位量
Horizontal displacement
10cm
震央 Epicenter
2016/10/21
余震 Aftershocks
(M > 2)
Analysis by GSI from ALOS-2 raw data of JAXA

Estimation of the coseismic slip history deduced from the “GNSS carrier phase to fault slip” approach

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Detecting aseismic slip within several hours to days is important for understanding a postseismic process in a plate interface. Conventional kinematic GNSS analysis, however, has disadvantage in such slow deformation, because it shows the large noise in the low frequency. Cervelli et al. (2002) developed the new method for such transient crustal deformation. They investigated the aseismic slip history of the fault in Kilauea volcano, directly from the GNSS carrier phase data. In contrast, there are small number of previous researches for the coseismic slip estimation based on their method. Thus, we applied their method (hereafter, PTS (Phase to Slip)) for the estimation of the coseismic slip history for the 2016 Kumamoto earthquake (M_{jma} 7.3) in this study.
The method of PTS used double-differenced carrier phase data as the observation. The observation related to the fault slip directly via the Green’s function. In the PTS, we adopted Kalman filtering approach for the unknown parameters estimation. We adopted the Green’s function solution to the elastic half space problem (Okada, 1992).
We used every 30s carrier phase data in eight GNSS stations (GEONET) in and around the focal area of the 2016 Kumamoto earthquake. For simplification of the inversion, we assumed the geometry of the single rectangular fault model estimated by Kawamoto et al. (2016). Then we assumed the white noise stochastic model with a process noise value 3×10^2 m $s^{-1/2}$ for the fault slip parameter.
As a result, we obtained the 3.6m coseismic offset within two minutes after the origin time. Obtained result, however, shows a slightly smaller than the result of Kawamoto et al. (2016), which reached 4.2m. Furthermore, our result clearly shows the long-period disturbance reaching approximately 1m. It should be caused by the difficulty of the strict separation between each unknown parameters such as the tropospheric delay and the fault slip. To avoid such problem, the adoption of the optimum process noise value for each unknown parameters is one of the possibilities (e.g. Hirata and Ohta, 2016).
In the presentation, we will describe the more detail characteristics of the PTS not only about coseismic behavior but also the time dependence of the postseismic one.

Estimation of postseismic deformation of 2016 Kumamoto earthquake based on GNSS observation network

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Postseismic deformation is mainly caused by the afterslip and viscoelastic relaxation, which assumed by the temporal evolution in logarithmic and exponential functions, respectively. To investigate the postseismic deformation associated with the 2016 Kumamoto earthquake (M7.3), we fitted these decay function to postseismic Global Navigation Satellite System (GNSS) time series. We used approximately 7-months (until 11 November, 2016 after the mainshock) of the daily coordinates of F3 solutions at 134 GEONET stations in Kyushu Island and Amakusa Island, provided by the Geospatial Information Authority of Japan (GSI). For the time series, we fitted logarithmic decay function for first 50-day, 100-day and 211-day after the mainshock using a nonlinear least-squares method to find appropriate amplitude of the function and time decay constants. The estimated time constants in this study correspond reasonably well with the values 0.8-36 days obtained in Nakao et al. (2016). It seems that the afterslip has ended in 50-100 days. Averaged time decay constants for this afterslip is estimated approximately 1.84-2.50 days. These are slightly bigger than the result of Takahashi et al. (2005) studied about 2004 mid-Niigata prefecture earthquake. Using the averaged time decay constants as a common value for all stations, we re-fitted logarithmic decay function and estimated special distribution pattern of amplitude. The result indicated large value not only around the focal region, but also more northeastern region from the epicenter. The residual time series extracted afterslip deformation shows linear trend at some stations, and time-dependent trend at other stations. When we assumed that this residual time series is caused by the viscoelastic relaxation, fitted exponential decay functions for them shows more than 10000 days of time constant around the focal area. It may reflect that viscoelastic relaxation is ongoing as of 11 November, 2016, or the applied fitting function is not appropriate for the residual time series. In the future, we may be able to quantitatively evaluate by prolonging the time series.

Keywords: 2016 Kumamoto earthquake, afterslip, viscoelastic relaxation

Vertical Deformation Detected by the Precise Levelling Survey after the 2014 Mt. Ontake Eruption (2014-2016)

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We conducted the precise leveling surveys in Ontake volcano in October 2014, April 2015 and September 2016 and discussed vertical deformations detected in the Periods of after the 2014 Mt. Ontake Eruption.
The leveling routes of about 38 km with 98 benchmarks were established on the eastern flank of Mount Ontake volcano. The main routes were extended to the Yashikino village (Kakehashi and Yashikino routes). In order to improve the spatial layout of the benchmarks, a branched leveling routes were established (Kiso-Onsen, Ontake Ropeway and Nakanoyu routes).
In the half year after the 2014 eruption (October 2014-April 2015), the small uplift less than 4mm was detected on the Ontake Ropeway route. In the period between April 2015 and September 2016, the uplift of 6mm and the small subsidence of 3mm were detected in the Nakanoyu and the Yashikino routes, respectively.
In the period of before the 2014 eruption (2006-2009), notable uplifts were detected on theYahikino and the Kiso-Onsen routes. The pressure source model based on this notable uplift was estimated to infer preparatory process preceding the 2014 eruption.
Although small uplifts were detected in the period of after the 2014 eruption, the spatial pattern of uplift is different from that in the period of before the 2014 eruption.
We need continued and careful observation of the deformation in Mt. Ontake volcano.

Keywords: Mt. Ontake, precise leveling survey, vertical deformation

Long term crustal movement estimated from glacio-hydro isostatic modeling and relative sea level observation

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Sea level observation can be used to track past crustal movement histories. A large number of studies have been conducted to obtain past sea level change information though quantitative analyses combining them to glacio-hydro isostatic adjustment (GIA) modeling is are rarely conducted. Thus, the long term vertical crustal movement estimation, which is an essential data to understand the tectonic stability, has not yet sufficiently been understood.
In this study, we compiled published sea level data (from more than 100 sites) and compare the values with GIA modeled sea level estimation in the past. We also revisited the possible range of rheology parameter of Earth, which is a source of GIA model based sea level uncertainty. Then the data were compared with GIA modeled sea level to evaluate the amounts of vertical tectonic movement from LGM to present.
We also estimated amounts of vertical tectonic movement longer than 100,000 years using the Last Interglacial marine terraces. This was then compared with the one from LGM and found the systematic trend depend of regions.
In this presentation, we discuss possible reason to provide these discrepancies.

Keywords: sea-level change, GIA, coastal terrace, vertical tectonic movement, last interglacial, LGM

