ALOS-2 contributions for detection of crustal deformation associated with earthquakes

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Analysis of SAR images is a powerful and unique remote sensing technique for detecting coseismic crustal deformation of earthquakes with spatially high resolution and without any ground based observation infrastructures.
Advanced Land Observing Satellite 2 (ALOS-2) is an L-band synthetic aperture radar (SAR) satellite, launched by Japan Aerospace Exploration Agency (JAXA) on 24 May, 2014. Observation capability of ALOS-2 is higher than that of ALOS, the predecessor of ALOS-2 and operated from 2006 to 2011, in terms of a revisit cycle (ALOS-2: 14 days, ALOS: 46 days) and attainable spatial resolution (ALOS-2: 3 m, ALOS: 10 m). Moreover, ALOS-2 can observe not only by common right-looking but also by left-looking, and ScanSAR interferometry is always applicable, unlike ALOS. These improvements enhances rapid-response after earthquake and detection capability of crustal deformation.
SAR Analysis Working Group of the Coordinating Committee for Earthquake Prediction is a group of experts which was established under the Coordinating Committee for Earthquake Prediction, Japan, in order to detect detailed coseismic crustal deformation through analyses of SAR images of ALOS-2, develop related techniques, solve seismogenic mechanism from the deformation field and seek ways to utilize SAR data for disaster response and mitigation. The Geospatial Information Authority of Japan (GSI) is serving as the Secretariat of the working group and summarizing activities of the WG to a report which consists of results of ALOS-2 analysis, contributions for monitoring earthquakes and research regarding three years of ALOS-2 operation.
In this paper, we will show ALOS-2 contributions based on SAR interferograms of significant earthquakes which were observed by ALOS-2 upon urgent requests from the WG and analyzed by GSI. Especially in 2016, detailed crustal deformations were detected along with several inland earthquakes including the 2016 Kumamoto earthquake and the earthquake of the Central Tottori (Mj6.6). We will show SAR ingerferograms and crustal deformation fields of these earthquakes.

Keywords: ALOS-2, SAR, Earthquake, Crustal deformation

Postseismic Deformation following the 1995 Kobe, Japan, 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, and claimed more than 6,400 fatalities. The source faults, trending in the NE-SW direction, are estimated beneath the foothill of the Rokko Mountains, which are located north of the city and the highest peak is 931 m high, but it has a dominant right lateral strike slip components. The Rokko Mountains may have been built by the motion of active faults, but the uplift during the 1995 earthquake may not be enough. Therefore there is a possibility that postseismic deformation contributes to the building of the Rokko Mountains.

In order to study the postseismic deformation following the Kobe earthquake, 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 them. Especially, temporal continuous GPS observation made by the Geographical Survey Institute (present the Geospatial Information Authority), 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. We made DInSAR and PSInSAR analyses of SAR images using ASTER-GDEM ver.2 or GSI DEM.

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 that uplifted by 20 cm coseismically. 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 east of the Rokko Mountains in the vicinity of the NE terminus of the source fault of the Kobe earthquake. The LOS increase is also confirmed by ERS-1/2, Envisat and ALOS/PALSAR images. These facts indicate 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.

Keywords: 1995 Kobe earthquake, Postseismic deformation, GPS, SAR interferometry, Rokko fault zone

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

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The 2014-2015 Bárðarbunga rifting episode is one of the largest event in Iceland. Previous studies have already reported that the earthquake swarm migrated from Bárðarbunga to Holhraun where the fissure eruptions occurred at northern edge of Vatnajökull 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 Jökulhlaups 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 Bárðarbunga rifting episode.

Keywords: Dike intrusion episode, Divergent plate boundary, Synthetic Aperture Radar, Iceland, Pixel offset technique

Crustal deformation of the 2016 October 21th M 6.6 earthquake in central Tottori prefecture.

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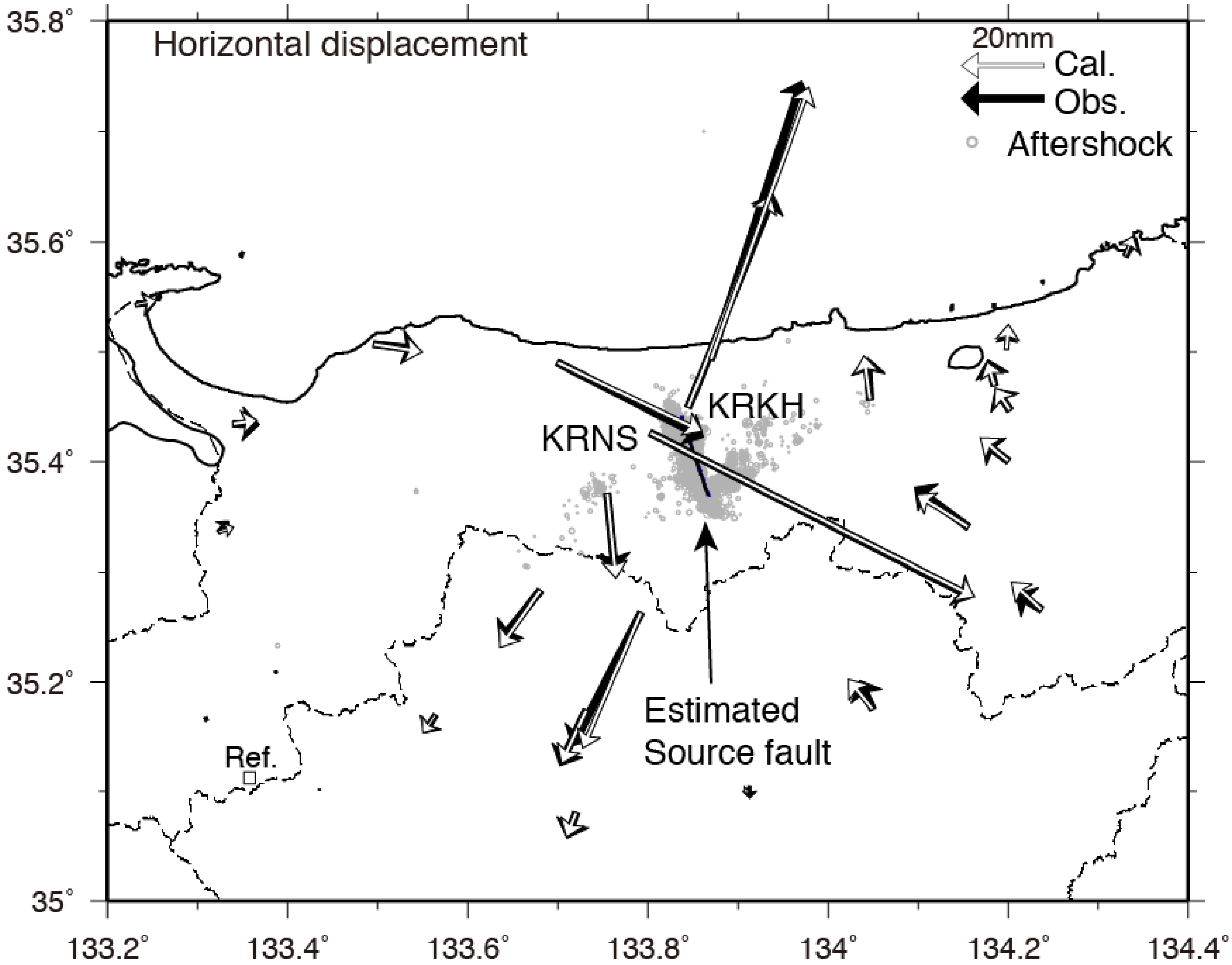
Introduction
There is a zone of active microseismicity along the Japan Sea coast in the San’ in region. Some large earthquakes including the 1943 M7.2 Tottori and the 2000 M7.3 western Tottori earthquakes also occurred in this seismic zone. Nishimura et al.(2014) showed a zone of high strain rate observed by GNSS almost overlapped the seismic zone and proposed to call it “the San’ in shear zone”.
We constructed 13 continuous GNSS stations in Tottori and Okayama prefectures 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_{JMA} 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.
Preseismic deformation
Deformation in the San’ in shear zone is characterized by right-lateral shear movements. GNSS stations along the Japan Sea coast moves eastward relative to those in Okayama prefecture. 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 deformation
Coseismic displacement was observed at GNSS stations in Tottori and Okayama prefectures (Figure). The largest displacement was observed at KRNS and shows horizontal displacement of 9 cm toward east-southeast and 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 deformation
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.

Keywords: Crustal deformation, GNSS, InSAR, San'in shear zone


Horizontal displacement
20mm
Cal.
Obs.
Aftershock
KRKH
KRNS
Estimated
Source fault
Ref.
35.8°
35.6°
35.4°
35.2°
35°
133.2°
133.4°
133.6°
133.8°
134°
134.2°
134.4°

Post-seismic deformation of 2016 Kumamoto Earthquake by continuous GNSS network

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The 2016 Kumamoto Earthquake (M 7.3) attacked to Kumamoto prefecture in Japan on April 16, 2016. Seismic intensity 7 was observed twice in the 2016 Kumamoto Earthquake. Post-seismic deformation was observed after the large earthquake occurred in land and trench. Twenty-one continuous GNSS observation sites were occupied after the 2016 Kumamoto Earthquake to observed post-seismic deformation. Thirteen of our twenty-one sites were near Futagawa and Hinagu fault zones, four of our sites were around Aso Volcano, which is east from Futagawa fault zones and the others were in Ohita Prefecture, which is east of Kumamoto Prefecture

Bernese GNSS Software Ver. 5.2 is used for GNSS data analysis of our newly sites together with GEONET and JMA GNSS sites for volcanoes in Kyushu for the period from April 15 to December 31, 2016. We used CODE precise ephemerides and CODE Earth rotation parameters. The coordinates of the GNSS sites are estimated respect to ITRF2008.

Large post-seismic deformation in horizontal component was observed at CGNSS sites near Hinagu and Futagawa fault zone. However, there is almost no observation in vertical component. Largest post-seismic deformation of 11cm from April to December, 2016 is observed in NS-component at MIFN, which is located east side of Hinagu fault zone. It seems that post-seismic deformation does not come to stop. After slip model is assumed for initial post-seismic deformation from April to July, 2016. We assumed two faults, one is located in Futagawa fault zone and the other is Hinagu fault zone. Fault parameters of length, width, strike, dip, amount of slip, position are estimated by simulated annealing method. Top and bottom of fault plane are 0.1 to 40 km in Hinagu fault and 0.8 to 32 km in Futagawa fault. Two fault planes extended to mantle. It suggests that there are several phenomena in initial post-seismic deformation, effect of viscoelastic etc.

Keywords: Continuous GNSS observation, post-seismic deformation

Afterslip, viscoelastic relaxation, poroelastic rebound: A possible mechanism in the sort and long term postseismic deformation following the 2011 Tohoku earthquake.

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Postseismic deformation of the Tohoku earthquake has been investigated by Ozawa et al. (2011), Wang et al. (2012), Diao et al. (2013), Sun et al. (2014), Perfettini and Avouac (2014), Shirzaei et al. (2014), Silverii et al. (2014), and Yamagiwa et al. (2015). Of these studies, Diao et al. (2013) investigated rheological model inferred from postseismic deformation of the Tohoku earthquake using 1.5 years GPS data following the mainshock. Because reliable investigation of the viscosity and its transient behavior require observation with longer time period, we build postseismic deformation model of the Tohoku earthquake using longer GPS data than that of used by previous studies and estimated the inferred rheological model. In addition, we also evaluate the possibility of the poroelastic relaxation signal due to the Tohoku earthquake.

We used observed surface deformation recorded by inland GEONET stations from 12 March 2011) to 12 October 2016 (~ 5.6 years). Afterslip model was inverted by assuming a homogeneous elastic half-space (Okada 1992). Viscoelastic relaxation due to coseismic stress change of the Tohoku earthquake is estimated using the Fortran code PSGRN/PSCMP (Wang et al. 2006). We estimated poroelastic relaxation following Gahalaut et al. (2008) and compared the result with observed ground water-level change to investigate relaxation time of poroelastic rebound.

Observed postseismic displacement for 5.6 following the mainshock show that deformation is characterized by seaward movement and is more broadly distributed than the coseismic displacement. Our model show an effective thickness of the elastic crust (D) and an asthenosphere viscosity (η) are 50 km and 5.6×10^18 Pa s, respectively. This result is consistent with most estimated viscosity in NE japan area (e.g., Rydelek and Sacks 1990; Suito and Hirahara 1999; Ueda et al. 2003; Hyodo and Hirahara 2003). Incorporating viscoelastic and poroelastic rebound in the early stage of postseismic deformation improve the agreement between predicted and observed displacement. It implies that postseismic deformation following the Tohoku earthquake is likely driven by multiple mechanism instead of single mechanism. Poroelastic relaxation is consistent with the ground water-level change during the first 140 days after the mainshock, suggesting that poroelastic rebound after the Tohoku earthquake have longer relaxation time than 60 days of poroelastic rebound following the 2000 South Iceland earthquake (Jonsson et al. 2003). Landward displacement of poroelastic rebound at offshore area indicate that this mechanism, along with viscoelastic relaxation, could have contributed to the postseismic deformation of the Tohoku earthquake.

Keywords: afterslip, viscoelastic relaxation, poroelastic rebound, GNSS, Postseismic deformation

Interseismic spatiotemporal change of the crustal deformation field estimated from GNSS around western coast of Tohoku region

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The eastern margin of Japan Sea is known as strain concentration zone from some geological and geodetic studies. Sagiya et al. (2000) found the “Niigata-Kobe Tectonic Zone (NKTZ)”, which is large strain rate field along Niigata to Kobe, analyzing GEONET data observed from 1997 to 2000 in whole Japan. Their result does not indicate remarkable large strain more northern region from Niigata, although relatively large strain rate is presumed by geological long-term period around the area. In addition, Yokota and Koketsu. (2015) suggests the possibility of the occurrence of the slow slip event around large area in Tohoku region before the 2011 Tohoku-oki earthquake from GNSS data analysis. This result implies that there are some abnormal spatiotemporal changes of the crustal deformation field during interseismic period in Tohoku region. After the NKTZ detection, GNSS sites are increased and more longer data can be obtained. In order to investigate spatiotemporal changes of the crustal deformation field in the interseismic period around Tohoku region including eastern margin of Japan Sea, we analyzed GNSS data at 194 stations of the GEONET. Using the F3 daily coordinates, we prepare every two-years coordinate time series and estimated velocity at each site fitting linier, annual and semi-annual trend. Obtained velocity data resolved to the subducting direction of the Pacific plate (N22°W), and plotted to velocity profile dividing 20 km-width area to north to south. As a preliminary result, we obtained velocity profile around west coast from north Niigata to south Akita. Southern part shows remarkable velocity change corresponding to the NKTZ area, meanwhile it is not clear in northern profile. Differences among two-years velocity profiles at same area were not clear excluding the case of temporal postseismic deformation after some inland earthquakes. To discuss detailed spatiotemporal change of the crustal deformation in Tohoku, we need information of more wider area of the velocity field.

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 Tohoku-Oki earthquake using GPS data in and around the Atotsugawa fault, located at the central part of Niigata-Kobe Tectonic Zone (NKTZ, Sagiya et al., 2000).
We used daily coordinates obtained from the GPS stations operated by university group in addition to GEONET by Geospatial Information Authority (GSI). For the pre-seismic period, we estimated the velocity field by removing annual and semi-annual components from the daily coordinates. For the post-seismic deformation, we extracted the period from 25 November 2014 to 2 July 2016, and estimated the velocity field in the same manner. For the co-seismic displacement, we calculated the average coordinates for 5 to 10 March 2011 and 12 to 17 March 2011, and subtracted the former from the latter. From the velocities and displacements thus determined, we calculated the strain rates following the method of Shen et al. (1996) with CCD of 20 km.
Spatial pattern of the co-seismic strain is completely different from the pre and post seismic strain rates pattern. The co-seismic deformation indicates elastic strain, and its spatial variation indicates heterogeneity in the elastic constants. Therefore we conclude that the pre and post seismic strain concentration is mainly caused by the inelastic straining. The strain rates before and after the earthquake are similar to each other, which can be explained by considering inelastic deformation responsible for the strain rate concentration. The inelastic strain, viscous flow for example, depends on the absolute stress accumulated over a long time scale, which is far larger than the stress change by one earthquake. The similarity in pre and post-seismic strain rates is consistent with a previous study for the northern part of NKTZ (Meneses-Gutierrez and Sagiya, 2016).
The deformation pattern before and after the earthquake are characterized by high strain rates along the Atotsugawa fault and its eastern and western ends where volcanic activity is high. In the volcanic areas, due to the high temperature, the viscous flow would be dominant. Along the Atotsugawa fault, on the other hand, the fault slip at the depth would be dominant. Thus, different mechanisms of inelastic deformation would proceed simultaneously in and around the Atotsugawa fault.
Looking in detail, we noticed some differences between pre and post-seismic strain rate pattern. For example, the sense of strain rates reversed 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. Considering these points, the change in the strain rates in these regions are probably related to the volcanic activities.

Keywords: Tohoku-Oki earthquake, GPS, inelastic strain

Estimation of postseismic deformation at the seafloor GPS-A sites following the 2004 off the Kii Peninsula earthquakes

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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]. However, in order to derive the stable velocities from GPS-A or GNSS data, the displacements caused by episodic events should be quantitatively estimated. Whereas the coseismic and postseismic deformations at the GPS-A sites associated with the 2011 Tohoku-oki earthquake had been already removed in the previous studies, the postseismic deformation of the southeastern off the Kii Peninsula earthquakes (on Sep. 5, 2004 JST, M_{JMA} 7.1, 7.4) have not been quantified. In this study, we constructed the FEM model to calculate the viscoelastic relaxation following these events. At first, we re-estimated coseismic finite fault source models, referencing the source parameters provided by Yamanaka [2004], Saito et al. [2010], Tadokoro et al. [2006] and Kido et al. [2006] for the mainshock, and those by Bai et al. [2007] and Yamanaka [2004] for the foreshock. The viscoelastic deformation was calculated using a 3D FEM model with a realistic subduction geometry. Whereas the oceanic slab and the continental lithosphere were assumed to be an elastic body, the oceanic mantle, the mantle wedge, and the weak asthenosphere which underlay the slab were assumed to have a bivisocous Burgers rheology. The displacements due to afterslip occurring around the rupture planes were also estimated to reproduce the residuals between observed and FEM-calculated viscoelastic displacements. Calculating the observation-calculated misfit values, the different parameter sets for viscosities of the mantle and the asthenosphere, and thickness of the continental lithosphere were tested. The preferred model with the lowest misfit value provided the southward displacements of up to 1 cm/year (between July 2006 and July 2009) in the Kumano Basin. Our result affects the estimation of the slip deficit rate in the Nankai subduction zone, such as provided by Yokota et al. [2016], where megathrust earthquakes have repeatedly occurred. In the presentation, we will show the possible impacts of these events and their postseismic deformation on the slip deficit estimate.

Keywords: Postseismic deformation, Finite element method (FEM) modeling, GPS-A seafloor geodetic observation, 2004 southeastern off the Kii Peninsula earthquakes, Viscoelastic relaxation

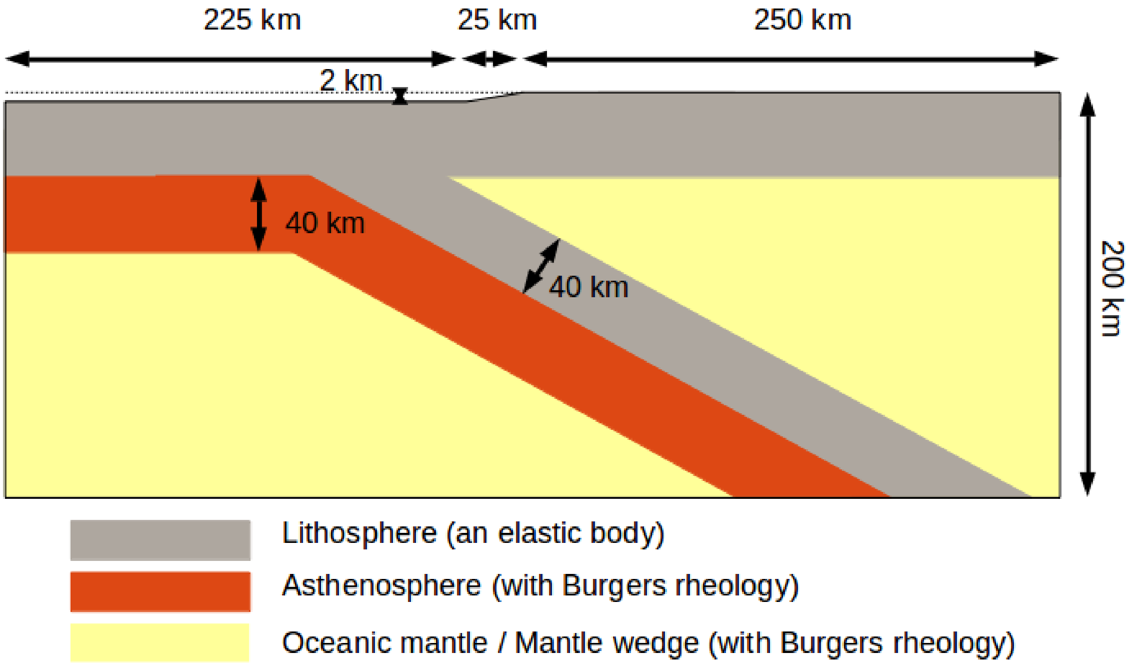

Fig. Schematic picture of FEM structure (cross section)

Vertical velocity profile and possible velocity changes in SW Japan from GNSS data over the last 20 years

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GNSS (Global Navigation Satellite System) observations have been playing a major role in studying crustal deformation near plate boundaries. Such observations provide valuable information on, e.g. fault mechanisms of earthquakes, and also contribute to mitigation of volcanic disasters. In addition to them, inter-seismic crustal deformation reflect strain accumulation in the plate interface, and enables us to study mechanical coupling between the plates. So far, most of these results are based on horizontal components of the 3-D crustal deformation, and the vertical components has not been well utilized. This would be due to the lower signal-to-noise ratio of the vertical crustal movements. On the other hand, in the plate boundary region, the horizontal components include both rigid plate motion and interplate coupling. On the other hand, the vertical components only contain the latter, and directly reflect inter-plate coupling. Aoki and Scholz (2003) analyzed the vertical crustal movement of the Japanese Islands using the data over three-year period 1996-1999. We already have 20 years of crustal movement data from the Japanese dense GNSS array GEONET (GNSS Earth Observation Network), and much more accurate vertical velocity data are available. In this study, we estimated vertical velocity using the time seris 1996-2016. In particular, we analyzed the interplate coupling in Southwest Japan using the vertical velocity profile spanning from the Muroto Cape to the Oki Islands. The interplate coupling in the Japan Trench is reported to have gradually weakened over the 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. The Nankai Trough is the plate boundary where the Philippine Sea plate subducts, and the next inter-plate earthquake is anticipated to occur within the coming years or decades. With the long-term data spanning ~20 years, we could study the temporal change of the vertical velocities. Here we modeled them using quadratic functions of time, and discusss the significance of the quadratic terms. GNSS stations close to the Nankai Trough subside while those a little farther apart show uplift. Then, the temporal change in the coupling would appear in various polarities and amounts for these stations. On the other hand, if the acceleration is simply due to some unknown movement of the reference point, the quadratic term would appear as a uniform value in all the station. In this study, I compared the linear trend and the quadratic components of stations with various distances from the trench, and found that the quadratic term might be a leakage from the movement of the reference point.

Keywords: Vertical Velocity

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.

Keywords: Crustal deformation, Southwest Japan, Philippine Sea plate, Median Tectonic Line, GPS

Block motion model in Colombia, using 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. Although, the effect of subducted Caribrian plate is not clear, the previous large earthquakes occurred along the subducting boundary of Nazca plate, such as 1906 (M8.8) and 1979 (M8.2). These previous earthquakes caused huge damage to life infrastructure and also lost the life along the subduction zone. 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 number of GEORED's GNSS site is increasing now. The sampling interval of almost GNSS site is 30 seconds, a part of GEORED is 1 second of sampling interval. In addition, there are campaign type of GNSS observations around the main active faults. A part of campaign type of GNSS observation was started at 1990's. 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). This definition of crustal block model is evaluated by Akaike's information criteria (AIC).

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. These results obtained rigid block motion model with linear problem. This model selection is based on AIC, which based on the number of parameters and residual between calculation and observation. In this presentation, we will discuss spatial interplate coupling ratio and also earthquake potential at inland faults.

Keywords: crustal block model, GNSS

Integrated analysis of GNSS data for volcano surveillances in Tohoku region, Japan

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GNSS geodesy techniques have been widely applied for monitoring volcanic deformations in the world, for example the 2010 eruption of Eyjafjallajokull, Iceland (Sigmundsson *et al.*, 2010), the 2011 caldera unrest of Santorini, Greece (Newman *et al.*, 2012) and the 2011-2012 eruption crisis of El Hierro, Spain (Lopez *et al.*, 2012). These case studies have deepened our understandings of magma supply system beneath volcanoes. In Japan, several institutes including Japan Meteorological Agency (JMA) has conducted GNSS surveillances in both continuous and campaign styles near active volcanoes whereas Geographical Survey Institute (GSI) has operated GEONET (e.g. Nakagawa *et al.*, 2009) which are widely distributed throughout Japan archipelago and mostly located far from volcanoes. Since in many cases, GNSS data have been analyzed independently by each institute with different strategies using different reference systems, there are rooms to discuss the consistency of the solutions. In order to obtain homogeneous solutions from far field to the vicinity of volcanoes, GNSS data sets of JMA and GSI are combined and analyzed with the same parameters and strategies. It is possible to evaluate whole volcanic system consistently using the combined data set which is sensitive to both the deep and the shallow depths. Bernese 5.2 software (Dach *et al.*, 2013) and IGb08 reference coordinates are used to obtain 24-hours solutions. In Tohoku region, in order to detecting volcanic signals, careful treatments are needed by properly evaluating the effects of postseismic deformation by the 2011 Tohoku Earthquake (e.g. Tobita 2016), the steady plate motions and the seasonal trends (Geirsson *et al.*, 2006). The 2014-2015 volcanic activity of Azumayama on the border of Fukushima and Yamagata prefectures has been analyzed by this study.

Keywords: deformation, GNSS, volcano surveillance, postseismic deformation, Azumayama

The role of depth-dependent background crustal viscosity in volcano deformation

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Geodetic (GPS and/or InSAR) observations have provided precise constraints on the mechanism that drives volcanic crustal deformation. Viscoelastic relaxation may play an important role in a long-term component of the deformation because in volcanic region the crustal viscosity is likely weakened by high geothermal gradient. A model with spatially uniform viscosity may be reasonably simple to examine the response of viscoelastic crust in a first-order approximation. But, in more detail, the crustal viscosity spatially varies in rich variety of ways, but the variation with depth is probably the most essential on which further variation would be superimposed, because the crust constitutes a part of the thermal boundary layer in which temperature increases with depth. This study investigates the role of depth-dependent viscosity (DDV) structure in viscoelastic crustal deformation by magmatic intrusion.

The linear Maxwell viscoelastic response of the crust and mantle to the inflation of a magmatic sill is solved, using a parallelized 3-D finite element code, OREGANO_VE [e.g., Yamasaki and Houseman, 2015, J. Geodyn., 88, 80-89]. The viscoelastic crust has depth-dependent viscosity (DDV) structure; the viscosity hc exponentially decreases with depth: hc = h0 exp[c(Zc - z)/L0)], where h0 is the viscosity at the bottom of the crust, c is a constant; c > 0 for DDV model but c = 0 for uniform viscosity (UNV) model, Zc is the thickness of the crust, z is the depth and L0 is a reference length-scale. The viscoelastic mantle has spatially uniform viscosity hm. For UNV model, so high viscosity is given to the uppermost layer with a thickness of H that it deforms in elastic fashion. DDV model however avoids having such an artificial elastic layer. The sill inflation is introduced by using the split node method developed by Melosh and Raefsky [1981, Bull. Seism. Soc. Am., 71, 1391-1400]. The geometry of the sill is approximated as an oblate spheroid whose depth is D, equatorial radius is W and thickness at the centre is dc. The inflation occurs instantaneously at time t = 0.

UNV model (c = 0) behaviour shows that an inflation-induced surface uplift abates with time by means of viscoelastic relaxation, whose subsidence rate is higher and slower if the sill is inflated at deeper in elastic and viscoelastic layer, respectively, and accordingly maximised by the inflation at the boundary between elastic and viscoelastic layers. The rate also depends on the artificially assumed elastic layer thickness H. DDV model (c > 0), on the other hand, shows that for a given c the subsidence rate is greater for greater D, which reflects the viscosity variation with depth. The available magnitude of the subsidence is greater for greater c, which is consistent with the UNV model behaviour that the subsidence is smaller for smaller H. Even if the viscosity gradient is very small, however, the model, having W and D being relatively small to a length-scale over which the viscosity decreases with depth, enhances the rate and available magnitude of subsidence as if the elastic layer is effectively thickened.

The DDV model behaviour requires an effective elastic thickness (EET) to be constrained for a given viscosity gradient in order to properly evaluate the deviation from UNV model behaviour. We thus in this study constrain EET by applying a UNV model behaviour that the post-inflation subsidence rate is slower for a deeper inflation if the inflation occurs in the viscoelastic layer. The DDV model is compared with a UNV model with H = EET, showing that at each surface point the UNV model approximates DDV model behaviour to some extent, but the apparent UNV which best fits the DDV model displacement history is smaller at greater distance from the centre of the uplift and that DDV model displacement is characterised by higher viscosity later in post-inflation period.

A new form of the equation system for geodyamics with clear and solid physical basis

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As the equation system for describing dynamical phenomena of the solid interior of the Earth such as mantle convection, plate tectonics and their interaction and so on, the equation system for Maxwellian viscoelastic media has been adopted so far. However, the idea that the interior of the earth behaves as a viscous fluid on long time-scales (e. g. Turcotte and Schubert, 2002) cannot be accepted from the simplest physical viewpoint that rocks are elastic solids in the usual sense of physics. Their dynamics must obey physical law of elastic solids regardless of time-scales. The origin of regarding long time-scale evolution of the solid earth as that of a viscous fluid might be similarity between creep of solids (including rocks) and motion of viscous fluids (e. g. McKenzie, 1967). However, creeping occurs as a result of transformation of temporal elastic strain into plastic permanent strain, often referred to as (elastic) stress relaxation. This is a physical process other than dynamical force balance, and hence it must be included in the basic equation system for geodynamics separately from the equation of motion. In the equation of motion, elastic force balances with other forces on long time-scales, where no viscous force is working. Starting from this system of two equations resultant mathematical expression becomes very similar to the equation of motion of viscous fluids if the rate of plastic displacement is identified with fluid velocity. Even with this similarity in recent numerical simulation studies treating mantle convection and plate motion together, in which fundamental unknown variable is fluid velocity, it is pointed out that behaviors of solid plates are not well simulated. In the proposed new form of basic equations the dynamical balance (equation of motion) is that of elastic solid so that this difficulty must be avoided. Further, in the new form dynamics equation is the one for elastic solid so that it can be extended to include brittle feature of the solid to generate fractures, i. e., earthquake and faulting. Thus new form of the basic equation system can be common basis for such important challenges in geodynamics.

Keywords: geodynamics, mantle convection and plate motion, Maxwellian viscoelastic media

Permeability heterogeneous structure nearby a fracture zone estimated by observed groundwater migration

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Permeability structure in a fault fracture zone might change due to seismic motion. However we have not realized the spatial scale of the change definitely. In this study, we observed pore pressure changes due to seismic motions at three sites in Rokko-Takao station which was established in a tunnel penetrating the fracture zone of Manpukuji fault, and estimated local changes in permeability structure nearby the fault fracture zone.
Groundwater migration is considered to mainly occur in a fracture zone, because permeability in that area is higher than the surrounding crust. Therefore, a fault fracture zone is approximately assumed to be one board with homogeneous permeability. Mukai et al.(2015) made a one-dimensional groundwater migration model and derived the method to estimate change in permeability by using changes in groundwater discharge and pore pressure. When we applied this model to the data obtained at Rokko-Takao station, we found that permeability in the fault fracture zone had been reduced during a few months just after the 2011 off the Pacific coast of Tohoku Earthquake. This result shows that a strong seismic motion propagated from a long distance could affect permeability structure in a fault fracture zone even though the fault was not an earthquake source fault.
To investigate the spatial distribution of groundwater migration, we newly installed two pore pressure meters in addition to the existing instruments in 2016. When we estimated permeability changes by using the observational data of pore pressure and groundwater discharge, we found that the permeability structure had changed just after the 2016 Kumamoto earthquake and the 2016 central Tottori earthquake as well. However the permeability changes depended on the location to observe the pore pressure, or the distance from the fault. For instance, just after the 2016 Kumamoto earthquake, permeability close to the fault rose by about 7%, while one in dozens of meters distance reduced by about 22%. This discrepancy might be caused by the outflow of mud due to the seismic motion. In the undeveloped fracture zone apart from the fault, the mud could be blocked and the permeability might be reduced, while the mud could flow out in the completely developed fracture zone nearby the fault.

Keywords: fault fracture zone, permeability structure, 2016 Kumamoto earthquake

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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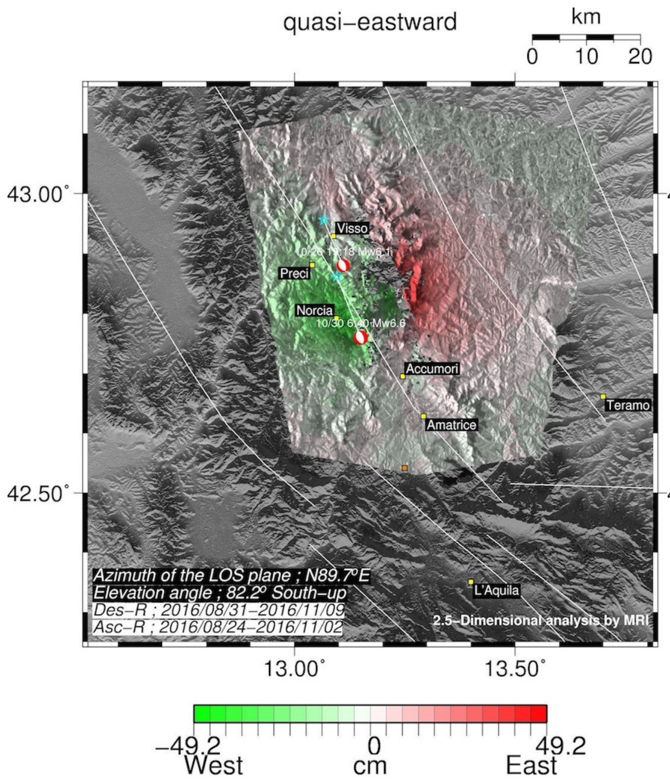
Three earthquakes of magnitude 6 classes occurred in the central of Italy on 2016 (August 24: Mw 6.2, Depth of 4.4 km - 10 km SE of Norcia; October 26: Mw 6.1, Depth of 10 km - 3 km NNW of Visso; October 30: Mw 6.6, Depth 8 km - 7 km N of Norcia). In any of the earthquakes, a lot of buildings collapsed 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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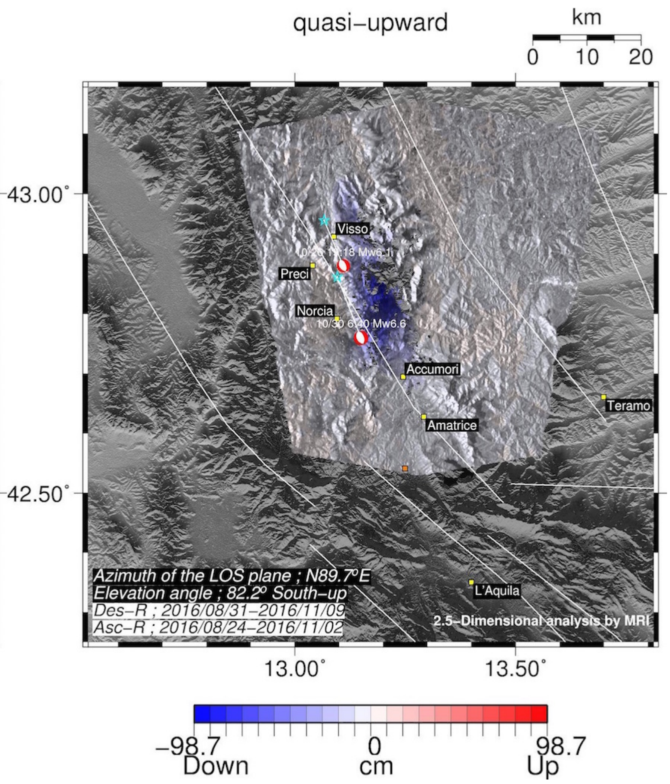
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Azimuth of the LOS plane ; N89.7ºE
Elevation angle ; 82.2º South−up
Des−R ; 2016/08/31−2016/11/09
Asc−R ; 2016/08/24−2016/11/02
2.5−Dimensional analysis by MRI
−98.7
0
98.7
Down
cm
Up

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.

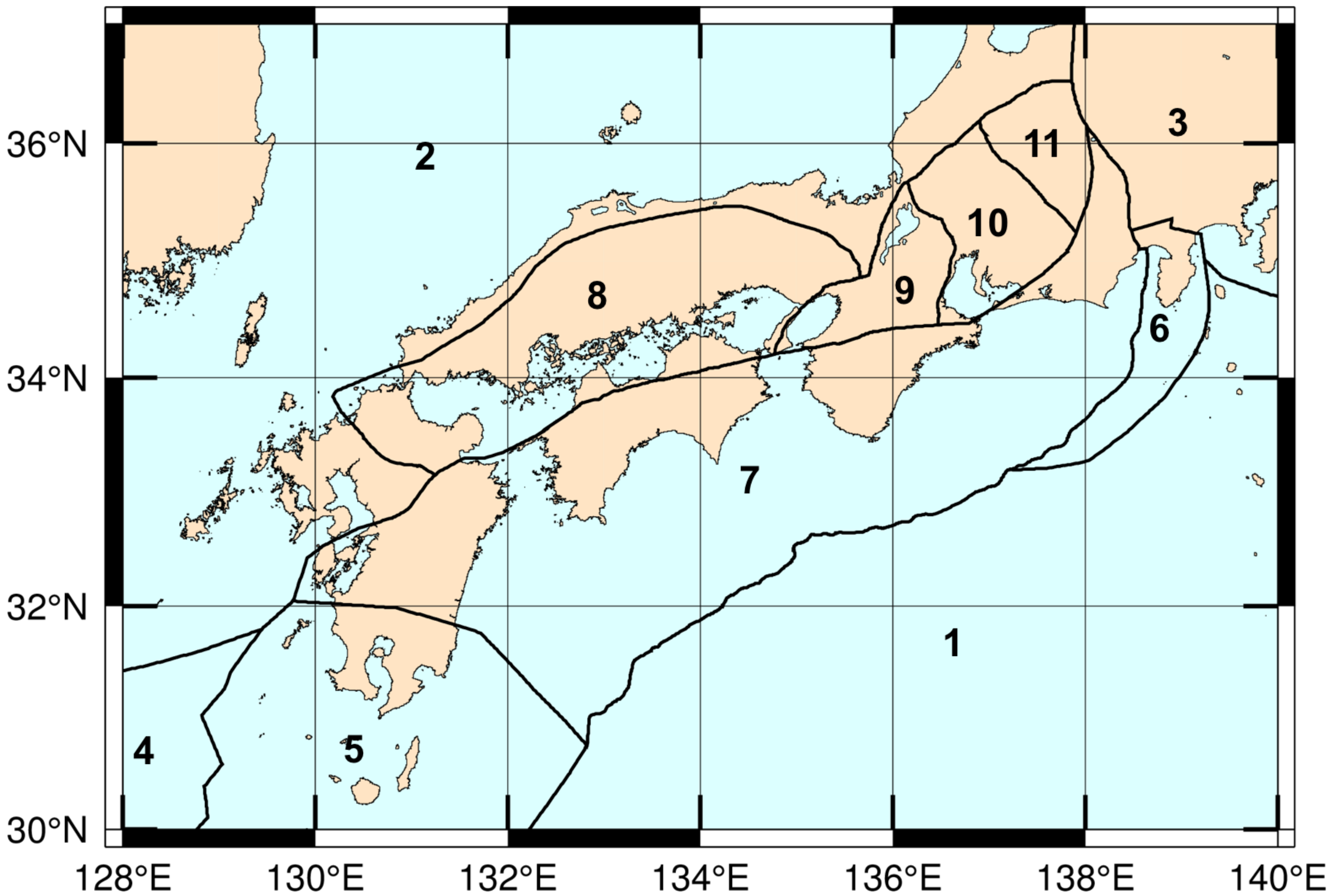
In this study, the coupling between the crustal blocks is estimated using the Markov Chain Monte Carlo method (MCMC). MCMC can evaluate the covariance between estimation parameters. This advantage is possible to evaluate the correlation between the slip deficit at the deep plate boundary and the crustal 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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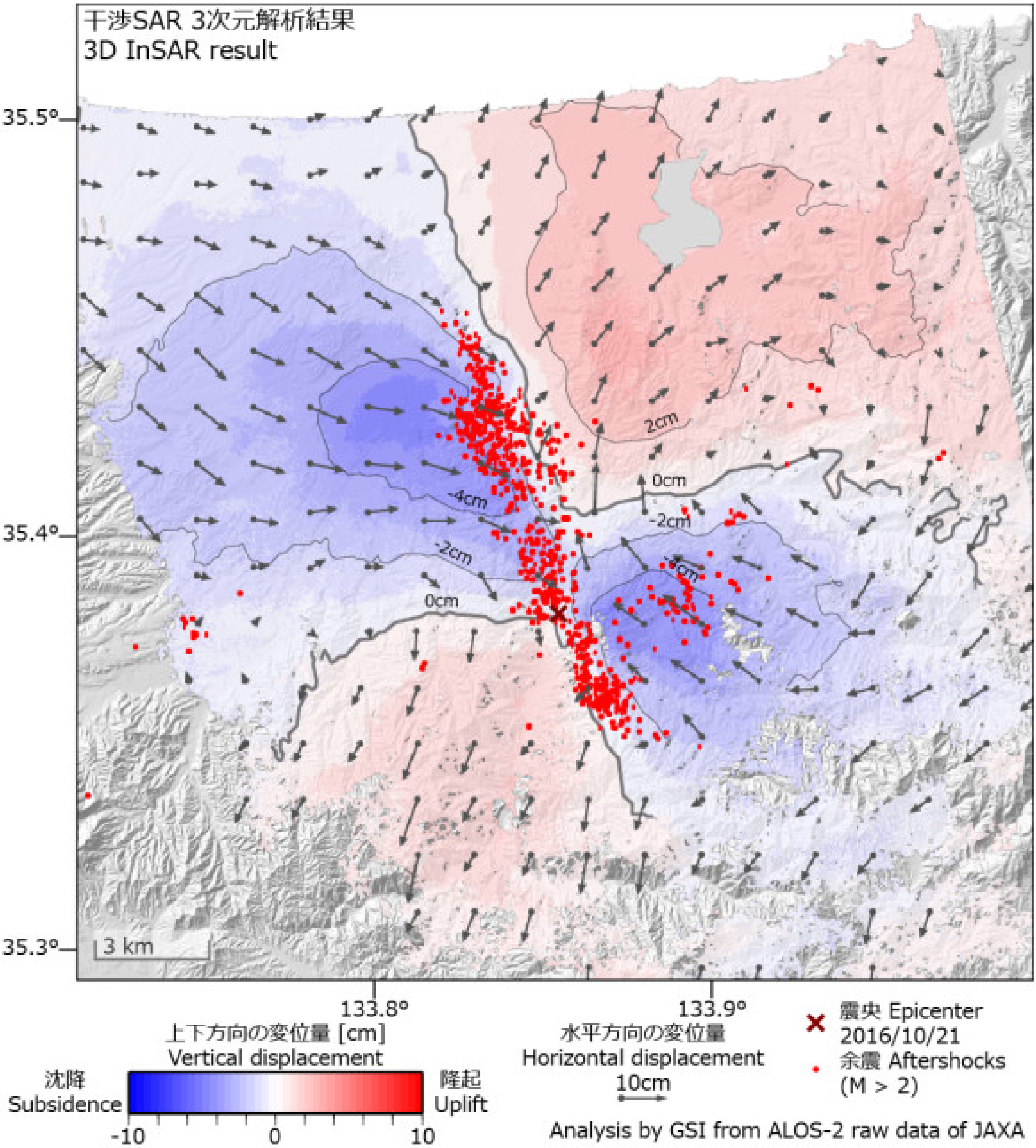
The Mj 6.6 inland earthquake occured on Oct. 21th, 2016 in the central Tottori prefecture, western Japan. Coseismic deformation derived from the earthquake was observed by GNSS and ALOS-2/PALSAR-2 interferometric SAR.
Continuous GNSS observation network (GEONET) is deployed in all over Japan with an 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 2.64×10^{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
-2cm
-4cm
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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1. Department of Earth and Environmental Sciences, College of Humanities and Sciences, NIHON University, 2. Graduate School of Environmental Studies, Nagoya University, 3. Graduate School of Science, Kyushu University, 4. Disaster Prevention Research Institute Kyoto University, 5. Graduate School of Science, Kyoto University, 6. Tono Research Institute of Earthquake Science, 7. Japan Meteorological Agency

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

