A crustal deformation model around the Izu Peninsula considering inland faults and elastic collision

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This study models crustal deformation focusing on inland faults and elastic collision around the base of the Izu Peninsula using GNSS(Global Navigation Satellite System) time-series data. First, in order to extract steady deformation, we correct the F3 solution data about antenna replacement from January., 2000 to January., 2010, and remove non-stationary variations using models of earthquakes, volcanic deformation and slow slip events. Next, we set elastic collisional power sources around the base of the Izu Peninsula, locking of plate boundaries, a deep creep of inland faults and a stationary volcanic deformation with a dislocation model and rotational motion of rigid bodies of the Izu micro plate and the Izu arc block (Nishimura, 2011). Then we perform an inverse analysis for the crustal deformation in this region.

The inversion result exhibits that elastic collisional power sources work at -12.7 mm/yr on the eastern foot of Mt. Hakone, 6.2 mm/yr on the northern foot, 11.6 mm/yr on the western foot and -0.5 mm/yr in the eastern Suruga bay. The plate boundaries are locked at 6 - 43.8 mm/yr beneath the Sagami trough, 3.6 - 39.3 mm/yr beneath the Suruga trough, 10 - 15.9 mm/yr in a southern edge of the Itoigawa Shizuoka Tectonic Line and 11 - 105.5 mm/yr on the boundary between the Izu micro plate and the Izu arc block. The inland faults creep at 23.3 mm/yr in deep extension of the Northern Izu fault zone and 23.4 mm/yr in deep extension of the Sagiriko Rokuroba fault group. In addition, the stationary volcanic deformation source at Mt. Mihara in the Izu-oshima island expands at 2.0×10^{6} m^{3}/yr. Furthermore, for the Honshu, the Izu mirco plate rotates at -3.1 °/Myr with the Euler pole of 36.57 °N, 139.72 °E and the Izu arc block rotates at -11.3 °/Myr with the Euler pole of 34.95 °N, 140.46 °E. The spatial variations of the elastic collisional power sourses correspond to actual terrain around the base of the Izu Peninsula.

Keywords: elastic collision, inland fault, plate subduction, volcanic inflation, Izu collisional zone, crustal deformation

Analysis of crustal deformation due to slip across faults using finite element method

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In Advance Soft Cooperation a computer program, named FrontSTR/GEOS, has been developed for the calculation of deformation due to fault slips and magma migration using finite element method. This program utilizes for the finite element calculation the program Front/STR that was obtained in the MEXT project "The Research and Development of Innovative Simulation Software" and contains some additional parts that have been developed by us to represent the effects of fault displacements and magma migration. In the finite element calculation displacements at nodal points are usually calculated in an iterative CG method. The program can be executed with a personal computer or a large computer allowing parallel computing.
The mesh for the finite element calculation is generated automatically in the following two steps by the program "meshgen" that has been developed by us. Namely, the region in question is first divided by hexahedron elements to make the whole mesh and then faults are put into the whole mesh. These two steps are independent so that we do not have to remember the whole mesh when we define faults.
The whole mesh consists of one or several blocks. Each block is divided by hexahedron elements whose sizes are constant or change at a constant rate with the location of the element. The surface topography can be taken into account by adjusting the thicknesses of the top elements. The effects of artificial boundaries placed on the sides and floor of the region can be made sufficiently small by introducing infinite elements along the boundaries. Elastic constants of each element can be set consistently with a three-dimensional distribution of seismic velocities.
The fault surfaces are defined by assemblies of triangles or quadrangles. The fault slip is specified at each vertex of the triangles or quadrangles and interpolated into their interiors. There may be more than one faults in the region but they cannot be intersected one another. Furthermore, each fault must stay within one of the blocks.
The elements through which one of the faults passes are further divided by the fault plane into some elements that have additional nodal points on the fault plane. Each of these new nodal points have double displacement values whose difference represents the slip or opening of the fault. In the finite element calculation the double displacement values are calculated with other displacements in the MPC method so as to meet both elastic equilibrium condition and prescribed constraints put on the double displacements.
The basis of our computer program is the calculation of elastic deformation due to prescribed displacement difference across the fault. The relaxation of viscoelastic deformation is traced with time based on the nature that the viscoelastic effect can be represented as an additional external force in the calculation of elastic deformation. The effect of gravity is taken into account in this calculation of relaxation. Some stress conditions on fault planes can be treated by adjusting suitably the constraints on the double displacements.
The program is applied to the deformation due to the fault slip during the great earthquake east off the northern district of Japan, March 11, 2011. The influence of fault geometry and slip distribution on crustal deformation is examined for this event. Relaxation of deformation after the event is evaluated under a suitable assumption of viscosity distribution. The merit in representing fault slip by double displacements is also demonstrated using this event.

Keywords: finite element method, fault slip, the great earthquake east off the northern district of Japan

Interseismic Crustal Deformation in Southwest Japan: Oblique Plate Convergence and Forearc Block Motion

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The Median Tectonic Line (MTL) is the longest arc-parallel strike-slip fault in southwest Japan, whose right-lateral motion originates from oblique subduction of the Philippine Sea plate (PHS) at the Nankai trough. MTL separates the forearc block from the rest of the overriding southwest Japan arc. Rate of relative block motion between them is estimated small enough compared with the dominant crustal shortening in the direction of PHS convergence since the interseismic coupling on the plate interface is generally strong. Nevertheless strain accumulation on the MTL fault plane is very important because it is capable of producing a major inland earthquake in the future. In this study, we simultaneously deal with elastic deformation due to strong coupling on the PHS interface, forearc block motion relative to the southwest Japan arc, and small shear deformation due to partial locking of the shallower part of the MTL fault plane.
We use horizontal and vertical displacement rates derived from GEONET final coordinate time series at 291 sites from Kyushu to Kinki regions during the period of 2004-2009. In addition we incorporate horizontal displacement rates from dense GPS campaign observations at 37 sites deployed along two traverse lines across the MTL. The PHS interface is reproduced by more than 1000 triangular elements from 5 to 60 km in depth. Similarly MTL is divided into four segments from east to west and each segment is modeled by a uniform rectangular plane with a dip angle of 50 degrees. Also the MTL fault plane is assumed to be partially locked from the surface to the depth of 15 km. We introduce Markov Chain Monte Carlo method (MCMC) for simultaneous estimation of parameters. The MCMC derives posterior probability density functions of unknown parameters from enormous forward calculations. These calculations are executed by random value sampling which are generated by Monte Carlo method based on Markov chain algorithm. Even in a case of the model with a large number of unknowns, we can estimate parameter values and confirm their validities. In our modeling, new constrains are introduced that forearc block motion relative to the southwest Japan arc is inherently parallel to the strike of MTL and slip-deficit rate on the MTL fault plane does not exceed the rate of the relative block motion across the MTL.
The results shows that distribution of interseismic slip deficit rates on the PHS interface is very similar to those obtained in several previous studies. The strongest-locked region (> 60 mm/yr) exists at the depth of 15-25 km under Tosa Bay just south of Shikoku, which nearly overlaps the main rupture zone at the last megathrust event in 1946. The rate of the forearc block motion relative to the southwest Japan arc is estimated as about 4 mm/yr westward. Locking of the shallow MTL fault plane shows slight lateral variation from east to west. We find that the eastern segment is nearly fully locked, then the locking weakens toward the west. It is interesting whether the results are related to the difference of strain accumulation rate and recurrence interval between the segments.

Keywords: Markov Chain Monte Carlo method, Median Tectonic Line, Southwest Japan, GPS observation

Tectonic and volcanic deformation at the Azores Triple Junction, observed by continuous and campaign GPS analysis

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The Azores archipelago is located at the junction where three tectonic plates meet: the Eurasian, Nubian and North American plates. It is an area of intense seismic and volcanic activity (Gaspar *et al*. 2015). The boundary between the North American and the other two plates is well defined, but the boundary between the Eurasian and Nubian plates is obscure. Previous geological, geophysical and geochemical studies have revealed diffuse and complex tectonic regime for this boundary zone. The use of space geodesy techniques, such as Global Positioning System (GPS), has provided important contributions to unveiling these diffusive plate boundary characteristics (Fernandes *et al*. 2004, 2006; Trota 2009; Marques *et al*. 2013) as well as detecting volcanic signals (e.g. Fogo Volcano - Trota 2009). The relation between regional tectonics and local volcanic activity is, however, poorly understood. Few attempts have been made to address the detailed spatial and temporal geodynamic processes. The accumulation of data in recent years at S. Miguel Island, is making such attempts possible.

We analyze 9 continuous GPS (CGPS) stations and the campaign data of the island for the period of 2008-2013 using Bernese5.0 software (Dach *et al*. 2007). In order to tie the estimated coordinates to the global geodetic reference frame - ITRF2005, neighboring international IGS station data are simultaneously processed along with the local datasets. By comparing with the current plate angular velocities (DeMets *et al*. 2010), we find a high-strain-rate (0.28 ppm/yr of expansion) zone in the east of Fogo volcano, which accommodates about 50% of the Eurasian-Nubian plate spreading.

Fogo exhibited intense seismic swarm during 2011-2012. The analysis of detrended GPS time-series after subtracting regional plate velocities reveals the existence of two different types of ground deformation associated with the seismicity. One is the edifice-scale inflation of Fogo, which corresponds to the increase in volcano-tectonic events. Another is inflation-deflation reversal in the east of Fogo, which coincides with the sharp decrease in lower-frequency events in August 2012. A strong similarity to the Matsushiro, Japan, earthquake swarm (1965-66) and Campi Flegrei, Italy, volcanic episodes (1969-72 and 1982-85) may suggest importance of the hydrothermal system at Fogo volcano. We propose the following hypothesis for the Fogo unrest: (1) the primary inflation source beneath Fogo promotes lateral diffusion of fluids that is selectively guided by existing cracks/fissures formed from regional extension; (2) an influx of fluids increases pressure in cracks/fissures and generates lower-frequency earthquakes; and (3) discharge of fluids causes pressure decrease and dilatancy recovery (i.e. seismic quiescence). To estimate the source parameters, the result of GPS campaigns is modelled by an integrated inversion using a genetic algorithm. The best fit model agrees well with the regional/local tectonic feature.

Keywords: crustal deformation, GPS, GNSS, plate tectonics, Azores, volcano geodesy

Visco-elastic relaxation in volcano deformation

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Satellite-based observation (GPS and/or InSAR) has precisely measured surface deformation, but by itself does not derives a mechanism of the deformation. We therefore need to employ some theoretical model in order to understand characteristic deformation pattern for a given source mechanism, only based on which the deformation source mechanism can be objectively deduced from the observation. Magmatic activity in depth is particularly considered as the source mechanism in this study. We employ a parallelized 3-D finite element code, OREGANO_VE [e.g., Yamasaki and Houseman, 2015, J. Geodyn., 88, 80-89], to solve the linear Maxwell visco-elastic response to a given internal inflation/deflation of magma chamber. In a rectangular finite element model domain, the crust is mechanically two-layered, in which an elastic layer with thickness of H is underlain by a visco-elastic layer, but the entire mantle behaves as visco-elastic material. A depth-dependent viscosity (DDV) is adopted for the visco-elastic crust, where the viscosity exponentially decreases with depth due to temperature-dependency: hc = h0 exp[c(1 - z/L0)], where h0 is the viscosity at the bottom of the crust, c is a constant; c > 0 for DDV model and c = 0 for uniform viscosity (UNV) model, z is the depth, and L0 is a reference length-scale. The visco-elastic mantle is contrarily assumed to have a spatially uniform viscosity hm. A sill-like magma chamber is approximated as a spheroid, and it inflation/deflation is implemented by using the split node method developed by Melosh and Raefsky [1981, Bull. Seism. Soc. Am., 71, 1391-1400]. We first employ UNV model with c = 0, which shows that visco-elastic relaxation abates the inflation-induced surface uplift with time; The post-inflation subsidence would erase the uplift in ~ 50 - 100 times Maxwell relaxation time of the crust unless the inflation occurs within the uppermost elastic layer. The rate of the subsidence is governed by a depth of the inflation and the equatorial radius of the sill; but the latter is not important for the earliest post-inflation period. Time-dependent inflation always accompanies with visco-elastic relaxation, and any significant surface uplift is not expected if the inflation has occurred over the time-scale greater than ~ 50 - 100 times crustal relaxation time. DDV model with c > 0 is also employed in this study to examine how a spatio-temporal deformation pattern at the surface is deviated from that for UNV model. The predicted model behaviour shows that UNV model behaviour approximates DDV model behaviour, but the apparent UNV which best fits a DDV displacement history depends on distance from the centre of the inflation; smaller viscosities are required at greater distances from the centre of the inflation. Such a model behaviour would expect that the spatio-temporal ground movement also depends on the depth of the sill inflation. Furthermore, a UNV model behaviour that the post-inflation subsidence depends on the thickness of the uppermost elastic layer requires us to examine the DDV model behaviour in terms of an effective elastic thickness for a given DDV structure. The model predictions obtained in this study provide important insights into geodetically detectable ground movement in volcanic provinces.

Keywords: Volcano deformation, Visco-elastic relaxation, Maxwell relaxation time

Crustal deformation by the West Off Satsuma Peninsula earthquake occurred on November 14, 2015

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The earthquake (JMA Magnitude 7.1) occurred on November 14, 2015 in the area of west off Satsuma peninsula. The epicenter is located in Okinawa Trough where is in about 160 km west from Makurazaki City in Kagoshima Prefecture. This earthquake is one of the largest earthquakes in this area. Seismicity in this area is low in last twenty years. Two continuous GNSS sites are operated by Kagoshima University, one is UJIS site in Uji island which is 84 km to east from the epicenter and the other is MESM site in Meshima island which is 121 km north from the epicenter. At UJIS seismic observation is also operated by Kagoshima University and it is operated by Kyushu University at MESM. We went to those sites in order to get GNSS and seismic data because GNSS and seismic data are not telemetered at those sites. In this research, co-seismic crustal deformation and activity of aftershocks are reported.We relocated the main shock and aftershock until 10:00 on November 16. Length of aftershock area is about 60 km. Its Strike is the same of Okinawa Trough. The epicenter of the main shock is located at the south-west end of the aftershock area and maximum aftershock, which is occurred on November 15, is at north-east end. Activity of aftershock in northern part of aftershock area is high. However, in southern part it is low except aftermath of occurrence of the main shock.GNSS data analysis is by Bernese GNSS software Ver. 5.2 with CODE precise ephemeris. Daily site coordinates of UJIS and MESM are calculated with GEONET sites. Coseismic deformation is estimated by the difference between two days averages before and after the main shock. Displacement at UJIS and MESM is 0.82 cm and 0.65 cm, respectively. The theoretical coseismic deformation is estimated by a strike slip fault model (Okada, 1992). Fault length, strike, dip angle and fault position are estimated by the length of aftershock area. Fault width is assumed a half of the fault length. Amount of fault slip is estimated by the relationship between earthquake magnitude and moment (Sato, 1979). JMA moment magnitude 6.7 is used (JMA, 2015). Theoretical displacement at UJIS and MESM is 1.3 cm and 1.1 cm. Direction of observed displacement is coincident with that of theoretical displacement. However, amount of observed displacement is smaller than theoretical one.

Surface deformation associated with the Meinong, Taiwan, earthquake

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A Mw 6.4 earthquake hit southern Taiwan on February 6, and claimed more than 100 casualties due to the collapse of building. In order to detect surface deformation associated with this earthquake, we analyzed ALOS-2/PALSAR-2 images provided by the Japan Aerospace Exploration Agency (JAXA). Post-event observations were made on February 9 and 14 with strip-map mode from the ascending orbit and with ScanSAR mode from the descending orbit, respectively. ScanSAR mode image covers the entire southern half of Taiwan including the epicenter. Therefore we can discuss total image of earthquake. We performed 2-pass interferometry with Gamma software with ASTER-GDEM ver. 2. In ScanSAR interferogram, we found a 20 km x 20 km are of increase of line-of-sight (LOS) up 9 cm and a 10 km (EW) x 20 km (NS) zone of LOS decrease up to 12 cm. The latter zone is also recognized in the strip-map mode interferogram, implying that this zone uplifted. These results are consistent with the GNSS observations and interpretation that the thrust motion on a shallow dipping decollement is responsible for this event (Ching et al, 2016, personal communication).
It is interesting that there is a zone of LOS increase sandwiched by two LOS decrease areas. There is a report that cracks were found in the peripheral region of this LOS increase zone (Ray Chuang, personal communication). This observation implies that a subsidiary faulting may have occurred near the western edge of decollement.
We also found LOS increase in northeastern part of the Tainan city. This area is an alluvial plane near a river. Therefore we suspect that liquefaction occurred in this area.
We will visit Tainan and make a field reconnaissance. We will report the results of field reconnaissance as well.
ALOS-2/PALSAR-2 images were provided by JAXA through the activity of SAR analysis Working Group of the Coordinating Committee for Earthquake Prediction. The ownership and copyright of ALOS-2/PALSAR-2 images belong to JAXA.

Keywords: 2016 Meinong Taiwan earthquake, surface deformation, SAR, ALOS-2/PALSAR-2

Block Rotation and Intra-plate Deformation in Java, Indonesia based on GPS observations

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Using the 1998-2013 horizontal velocity field including continuous and campaign Global Positioning System (GPS) phase data, we interpret the kinematics of Sunda Block and the present deformation of Indonesia. Four major earthquakes, the 2006 Java (M7.7, e.g. Ammon et al., 2006), The 2009 West Java (M7), and the 2012 Indian Ocean earthquakes (M8.6 and 8.2) occurred around southern boundary of the Sunda Block that affected the horizontal velocity field within the block. Since we only have the short span of time series for several sites especially in the Java island, we should remove the offsets and the exponential or logarithmic trends in the time series due to the earthquakes. By means of TDEFNODE (McCaffrey, 2009), we invert GPS site velocities simultaneously to estimate the Euler rotation parameter of blocks, earthquake slip vectors, and uniform horizontal strain rate tensor within the blocks. We constructed several block models for the Sunda Block kinematics and deformations. We assume one to four faults extending from the western part off the southern coast of Java and estimate the slip distributions. We also assume the different constraints on the nodes on these faults. From a series of the block models, we determine a preferred model by applying F-distribution tests between two models. The preferred model here is the one consisting of four faults along the java trench with unconstrained nodes without a homogeneous strain rate tensor, and produces the reduced chi-square of 0.754. This model generates the Euler rotation parameters of 48.917 ºN for latitude, 86.876 ºW for longitude, and 0.330 ±0.002 º/Myr for angular velocity with an error elliptic axes of 0.96º and 0.15º for the pole location. The distributions of interseismic locking on the plate boundary along the Java trench demonstrates the low coupling rate of ~30 mm/yr in the western part, the very low rate <10 mm/yr in the middle part, and the very high rate of ~65 mm/yr in the eastern part. The residual velocities derived from this model indicate the effect of the postseismic deformation in the western part of Java and the extensional pattern in the eastern part of Java, which may suggest volcanic deformation.

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Keywords: Sunda Block, Euler rotation, Block kinematics

Vertical displacement in Naruko Volcano area after the 2011 Tohoku earthquake deduced from precise leveling survey

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Great East Japan Earthquake occurred on 11 March 2011, causing large crustal deformation in the Tohoku region. GEONET observed subsidence exceeding 1m at Pacific coast and becoming smaller toward west (http://www.gsi.go.jp/common/000059956.pdf). To detect the vertical displacement inland, the first leveling survey was conducted in Naruko area, Miyagi prefecture, on east-west direction using a second-order leveling route along the National Route 47 for 10km in August 2011, as a part of summer field seminar by the Division of Earth and Planetary Material Science, Tohoku University. Contrary to the expectation before the survey, the subsidence increased westward in this section as compared with the leveling results in 2009 by Geospatial Information Authority of Japan (Tsukamoto et al, 2014). By In-SAR analysis, Ozawa and Fujita (2013) and Takada and Fukushima (2013) showed that Kurikoma-Naruko volcanic region subsided locally coincident with the earthquake. The westward relative subsidence detected by the leveling was in harmony with these results. The second leveling survey in August 2013 showed that further subsidence had progressed on the same route, and the displacement pattern was almost similar to that in 2011 (Tsukamoto et al, 2014).

To detect the subsequent displacement, we made the third precise leveling survey on 27-31 August 2015 on the same leveling route (benchmark number 047-064, 066, 068, 070, 072, 074 from east-west; hereafter indicated as BM64, BM66, etc.). We used bar-code leveling rods (Leica GPCL3) and an electronic digital level (Leica DNA03). We conducted round-trip survey between each benchmarks, and all residual errors fell within the acceptable range of the first-order leveling.

Relative to August 2013, BM66, BM68, BM72, and BM74 subsided 7.6 mm, 14.6 mm, 31.8 mm and 36.2 mm, respectively, against the eastern end BM64. These indicate westward-growing subsidence has continued (or probably is still continuing) along the survey route after August 2013, although the deformation rates have decelerated. The only exception is BM70; subsidence had changed into 4.6 mm uplift. This is the only uplift we have detected on this survey route since the 2011 Great Japan Earthquake.

Postseismic vertical displacements detected by GPS array, equipped semi-parallel to National Route 47 by Tohoku University, indicate that the surveyed area corresponds the transition zone from eastern uplift to western subsidence. Relative to the GPS station 0174 whose longitude is close to that of BM64, the next two western GPS stations collateral to the survey area have been subsiding, which is in harmony with our survey results. On the contrary the uplift such as seen at BM70 is undetected.

Leveling surveys in 1969 and 2009 by the Geographical Survey Institute indicate that BM70 subsided against BM68 while BM72 and 74 uplifted during this period. According to Prima and Yoshida (2010) and Ogawa et al. (2014), the eastern edge of the rim of Naruko caldera crosses between BM68 and BM70. The unique behavior of BM70 may be caused by such local geologic structure.

Keywords: Great East Japan Earthquake, Naruko caldera, precise leveling survey, subsidence

Precursory Strain and Tilt Variations of Earthquake Swarm Occurring in Izu Peninsula in March 1997 and Occurrence of M5.5 Earthquake.

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Izu Peninsula is located at about 100km southwest of Tokyo. Earthquake swarms occurred in 1995, 1996, 1997 and 1998. We analyzed data observed by multi-component borehole instrument installed at swarm occurring area. The instrument equipped with strain meters, tilt meters, seismometers, magnetometers and a thermometer. Preliminary analyses were already reported. This time we investigated earthquake swarm occurring in1997. Earthquake swarm started about 10:30 3/3 1997.
Some results obtained are as follows:
1. Depth of hypocenters became shallower with about rate of 200m/hour after swarm occurred.
2. Descending vectors of tilt indicate that after March 2nd vectors show abnormal variations and after the occurrence of swarms variation accelerated and M5.5 earthquake occurred.
3. Principal strain variation recorded abnormal variations after the swarm occurred and variation accelerated and
M5.5 earthquake occurred.
4. Variations of tilt and strain become clarified from the beginning of occurrence to the end.
We also discuss relationship between earthquakes and tilt/strain variations.

Keywords: Precursory Phenomena, Earthquake Swarm in Izu Peninsula, Multi-component Borehole Instrument for Crustal Activity Observation, Strain Variation, Tilt Variation

Permeability change due to the earthquake estimated by using atmospheric effect on groundwater migration

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Groundwater migration due to atmospheric loading variation is dependent on hydraulic property in aquifer. Therefore, observed atmospheric effects on groundwater discharge and pore pressure have some information about permeable structure in the surrounding crust. In this study, we estimated permeability and storage coefficient changes due to the 2011 off the Pacific coast of Tohoku Earthquake by using atmospheric effects on groundwater discharge and pore pressure observed in the fault fracture zone, and considered cause of their changes.
Groundwater migration due to atmospheric loading is considered to mainly occur in a fracture zone, because permeability in that area is higher than the surrounding crust. Mukai et al.(2015) made a one-dimensional groundwater migration model, in which groundwater is assumed to migrate laterally in fracture zone, and derived the theoretical equation showing frequency dependence of atmospheric effect on groundwater discharge. When this theoretical equation is applied to the observed atmospheric effect on groundwater discharge, we can estimate change of value 'k*S' multiplying permeability 'k' by storage coefficient 'S'.
We can also obtain the theoretical equation showing frequency dependence of atmospheric effect on pore pressure by using the above groundwater migration model. One of the variables for this theoretical equation is 'S/k' dividing storage coefficient 'S' by permeability 'k'. Thus, it is possible to estimate permeability and storage coefficient independently by analyzing both atmospheric effects on groundwater discharge and pore pressure.
We estimated change of permeability and storage coefficient in the fracture zone of Manpukuji fault, which is penetrated by the Rokko-Takao station, by using groundwater discharge and pore pressure observed at the station as well as atmospheric pressure on the ground at the Kobe local meteorological office in period from August 2010 to December 2011. In this estimation, we first divided the period into some sections with length of 512 data (21.3 days) and calculated frequency dependence of atmospheric effect for each section. Secondly we applied the theoretical equation on the one-dimensional groundwater migration model to the observed atmospheric effects, and estimated permeability and storage coefficient changes as the most adequate model parameters.
Estimated storage coefficient increased by 3 times just after the earthquake. Mukai and Otsuka (2012) estimated change of groundwater source pressure by using the model on groundwater migration from the source to the station. They reported that the groundwater source pressure decreased just after the earthquake and had not recovered for a few months. These results suggest that seismic motion induced outflow of mud accumulated in the cracks and excessive outflow of groundwater in the groundwater source and the surrounding crust.
Estimated permeability decreased by about 40% just after the earthquake. This result appears to disagree with the above conjecture that seismic motion induced the outflow of mud. This disagreement might be caused by inhomogeneous variation in permeability in the crust. It is considered that the permeability estimated in this study shows that near the station, because periodic atmospheric loading causes groundwater flow in a small scale. The mud outflow owing to seismic motion might have been concentrated near the station where groundwater discharge occurs, which in turn might have caused the decrease in permeability in that area.

Keywords: permeability change, groundwater migration, 2011 off the Pacific coast of Tohoku Earthquake

Real-time monitoring of crustal deformation

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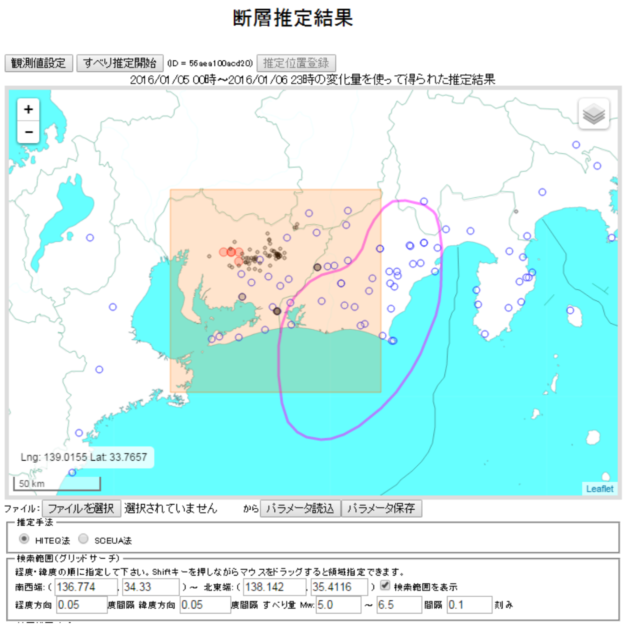
Japan Meteorological Agency is equipped with the new computer system to monitor crustal deformation, earthquake and tsunami. One of the purposes of this system is to detect precursor of the Tokai earthquake quickly and automatically. We introduce the stacking method (Miyaoka, Yokota, 2012) and the new idea which reduces ‘ghosts’, artificial changes of stacking data. The new system helps us to detect anomalous changes of plate boundary earlier.

Keywords: strainmeter, stacking, slow slip event



Characteristic of inland strain anomalies caused by the postseismic deformation immediately after the 2011 Tohoku-Oki earthquake based on kinematic PPP data analysis

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We have investigated spatial and temporal development of anomalous crustal strain in the northeastern Japan region associate with a postseismic deformation immediately after the 2011 Tohoku-Oki earthquake. Ohzono et al. (EPS, 2012) found the characteristic strain anomalies associate with the step-like stress change caused by the large coseismic displacement. Their results, however, should contaminate the crustal deformation by the early postseismic within one day.

Based on these backgrounds, we adopted the kinematic precise point positioning (PPP) analysis for understanding the crustal deformation caused by the early postseismic immediately after the mainshock. We used GIPSY-OASIS II Ver. 6.3 software for kinematic PPP processing of whole GEONET sites in 10 March 2011. We applied every 6 hours nominal wet and dry zenith tropospheric delay value as a priori information based on the ECMWF global numerical climate model. For the coordinate time series and tropospheric parameters, we assumed white noise and random walk stochastic process, respectively. These unknown parameters are very sensitive to assumed process noise for each stochastic process. Thus, we searched for the optimum two variable parameters; wet zenith tropospheric parameter and its gradient.

Furthermore, we applied the principal component analysis for eliminate the spatial correlated noise from the kinematic PPP time series. The strain calculation from the displacement data is based on the method developed by Shen et al. (JGR, 1996). Obtained dilatation strain clearly shows the inhomogeneous distribution. Compared with the seismic tomography results by Nakajima et al. (JGR, 2001), large expansion area by this study mostly just correspond to the low Vp region at the 10km depth. This results suggested that these localized expansion areas correspond to the lower elastic moduli in the upper crust and/or shallower portion. Furthermore, we assessed the amount of strain anomalies by the early postseismic deformation relative to strain anomalies by the coseismic deformation. Our early postseismic results suggest that the 20-30% of strain anomalies by Ohzono et al. (2012) may by caused by the postseismic deformation. This result suggested that the early large postseismic deformation behaved as “step-like” stress change to the crust as well as the coseismic deformation.

Surface movements immediately before and after the 2011 Tohoku-oki earthquake from kinematic solution of GNSS and thermal expansion of the pillars

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The Tohoku-Oki earthquake (Mw9.0) occurred on March 11, 2011, and fault dislocation at the Japan Trench caused large eastward surface displacement of the Japanese Islands. Ohta et al. (2012) reported displacement of GNSS stations in NE Japan with the time resolution of three hours just before the Tohoku-Oki earthquake. Hino et al. (2014) reported high time-resolution vertical movements of the seafloor close to the epicenter using ocean bottom pressure gauge. Hirose (2011) analyzed the Hi-net tiltmeter data just before the Tohoku-oki earthquake. All these observations showed clear signatures of the afterslip of the foreshock that occurred two days before the main shock, but did not show any anomalous movement immediately before the earthquake.
For time periods just after the earthquake, Munekane (2012) reported kinematic analysis results of GNSS stations in NE Japan, and identified signatures of crustal deformation associated with several large foreshocks and the afterslip of the main shock fault. Mitsui & Heki (2012) analyzed periodic surface movements caused by the Earth's free oscillation. In addition to these "real" crustal movements, Munekane (2012) identified uniform horizontal displacement signatures, and inferred that they originate from differential thermal expansion of GNSS pillars due to direct sunlight.
In our study, we try to investigate spatial and temporal correlation between the sunshine and thermal-expansion origin horizontal displacements (see the attached figure). Here we used the 30-second position data of the GEONET station in NE Japan obtained using the RTnet software package by Dr. T. Iwabuchi, UNAVCO. This is the same data set that Mitsui and Heki (2012) used. We also use the weather data available from the website of Japan Meteorological Agancy (http://www.data.jma.go.jp/risk/obsdl/index.php).

Description about the attached figure

[A]:Position change of the GNSS station (JST 12:00-13:00) by kinematic solution.
[B]:The sunlight hour (JST 12:00-13:00) by AMEDAS.
[C]:Solar Azimuth at every each hour.

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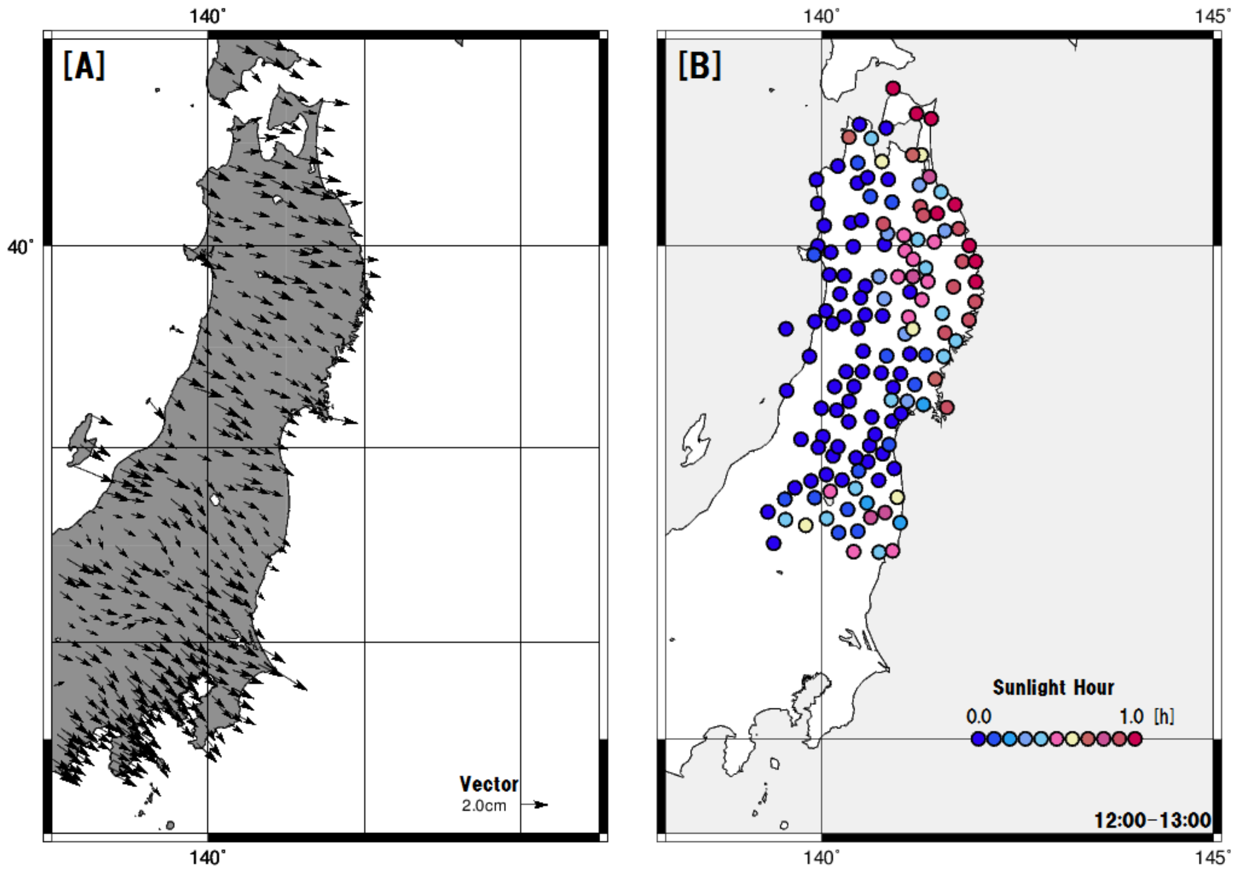
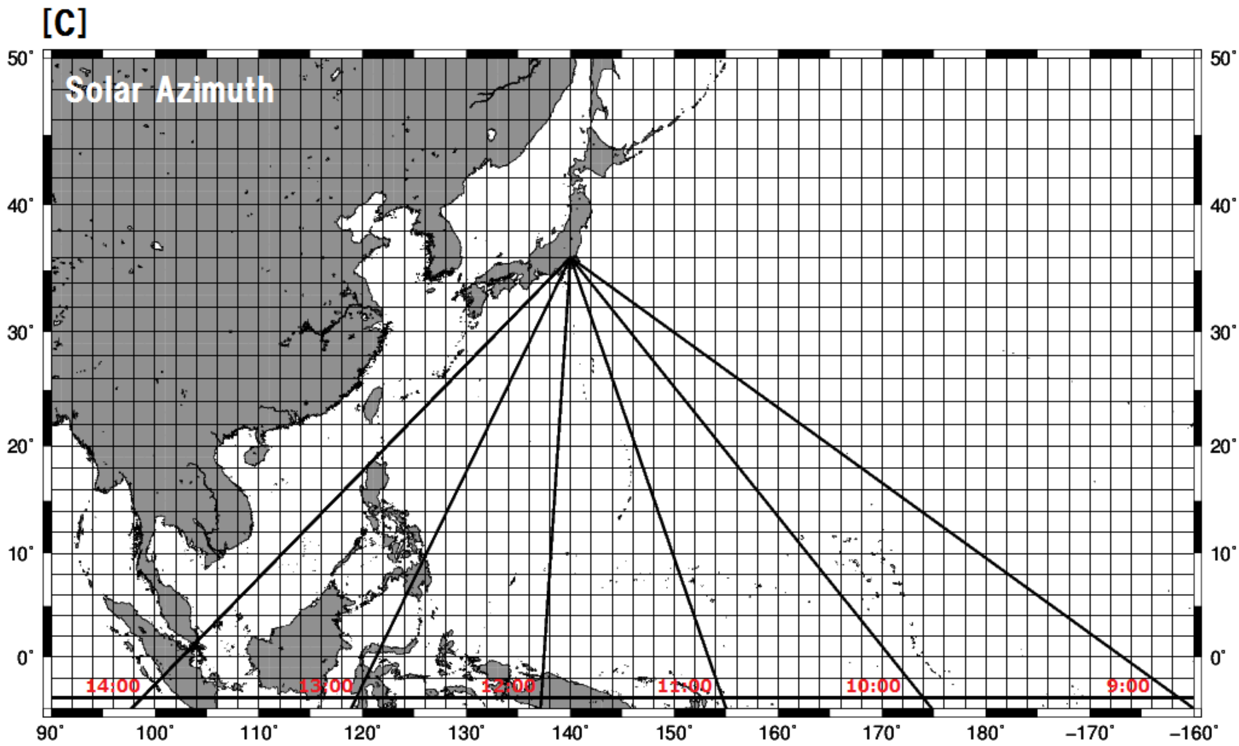
Keywords: crustal movement, GNSS, thermal expansion





Change of crustal deformations after the 2011 Tohoku-oki earthquake

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Large displacements induced by the great earthquake occurred on March 11, 2011, were observed by GEONET over the entire Japanese Islands. The maximum horizontal displacement observed by the GEONET reaches 5.4m at the tip of the Oshika peninsula. The subsidence up to 1.1m was observed by the land GPS along the Pacific coast. The postseismic deformations caused by this great earthquake are still lasting over the northeast and central Japan area.
We report the change of postseismic deformations following the 2011 Tohoku-oki earthquake. We also report the mechanisms of these postseismic deformations.

Keywords: 2011 off the Pacific coast of Tohoku earthquake, postseismic deformation

Insight into poroelastic rebound deformation following the tohoku earthquake

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K. Wang, Hu, and He (2012) proposed 3 primary processes that dominate the deformation following an earthquake at subduction zones; (1) afterslip, (2) viscoelastic relaxation, (3) re-locking of subduction fault. However, if the upper crust was saturated by fluid, the crust must be treat as a fluid-saturated poroelastic medium instead of elastic medium. Coseismic stress change disrupt pore fluid equilibrium and cause fluid migration from high pressure to zone of low pressure. Fluid migration drive transient surface deformation which is known as poroelastic rebound. Pore fluid flow induced by coseismic stress change is usually ignored due to the fact that; (1) this effect occurs in short time at early postseismic deformation just around the rupture area, (2) and no clear evidence of fluid-rich existence in the upper crust of the rupture. Due to the fluids-rich existence detected in the upper crust (Z. Wang, Huang, Zhao, & Pei, 2012; Yamamoto, Obana, Kodaira, Hino, & Shinohara, 2014; Zhao, Huang, Umino, Hasegawa, & Kanamori, 2011), pore fluid flow induced by coseismic stress change can produce contribution to the surface deformation.
Therefore, poroelastic rebound should be included in the analysis of early postseismic deformation following the Tohoku earthquake. Previous modeling studies in poroelastic rebound used various values for undrained and drained Poisson’s ratio (e.g., Peltzer, Rosen, Rogez, and Hudnut (1998); Jonsson, Segall, Pedersen, and Bjornsson (2003)). Instead of just assuming the values of drained and undrained Poisson’s ratio, we use grid search to estimate undrained and drained Poisson’s ratio value by combining forward calculation of poroelastic rebound and afterslip inversion of inland and offshore GPS data. In total, we build 400 poroelastic rebound model with different combination of undrained and drained Poisson’s ratio. Grid search approach obtained optimum value of 0.23 and 0.29 for drained and undrained Poisson’s ratio, respectively. Poroelastic rebound produced by the optimum value of drained and undrained Poisson’s ratio estimated horizontal displacement up to 0.28 m in the rupture area. Majority of large uplift due to poroelastic rebound occurred in and around the vicinity of the rupture area where maximum uplift estimated up to 0.37 m around the maximum slip area of the mainshock.

Keywords: poroelastic rebound, undrained and drained Poisson's ratio, grid search, co- and after-slip inversion

The slow slip event in the Tokai region, central Japan, since 2013 as seen from GPS data

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Advent and developments of continuously operating dense GPS arrays have enabled us to detect aseismic transient slow slips called as slow slip events (SSE) that occur along the subducting plate interface. SSE has been discovered in Bungo Channel, Boso Peninsula, Tokai region and Ryukyu region in Japan. Moreover, short term SSEs have been found using the data of tiltmeters in the Hi-net seismic network in the southwestern Japan. These short-term SSEs are often accompanied by non-volcanic or deep low-frequency tremors.
In the Tokai region, the previous long-term SSE occurred from 2000 to 2005, the longest SSE ever found. Ozawa and Yarai (2014) suggested the possible next SSE started to occur near the previous occurrence location in the beginning of 2013. Therefore, in this study, we analyzed the GPS data in the Tokai region to estimate the temporal evolution of the current event. The data for the period from 1 January 2008 and 30 April 2015 was used. The GIPSY-OASIS II software was used for estimating daily coordinates of the 226 GPS stations from the GEONET in the Tokai district. Then, the coordinate time series were fitted with linear trend and seasonal variations for the period before the 11 March 2011 Tohoku-oki earthquake (Mw9.0). The obtained linear trend was extrapolated to the end of data, 30 April 2015, and was subtracted from the original coordinate time series.
Then, the effects of the post-seismic deformation due to the Tohoku-oki earthquake were removed by fitting the data from 11 March 2011 to the end of the data with simple mathematical functions, not considering physical processes of the post-seismic crustal deformations. We employed a logarithmic function and a logarithmic plus exponential function to model the post-seismic deformation and found that the latter fits the data significantly better. We thus used the logarithmic plus exponential function to model and remove the post-seismic deformation.
After removing the post-seismic effects by the above pre-processing, we applied the time-dependent inversion method to the data to obtain the spatio-temporal evolution of slip beneath the Tokai region. For this purpose, we used a modified Network Inversion Filter (NIF) (Fukuda et al., 2008), which is a modification of the original NIF (Segall and Matthews, 1997). The original NIF assumes a constant hyperparameter for the temporal smoothing of slip rate and thus results in oversmoothing of slip rate. The modified NIF assumes a time variable hyperparameter, so that changes in slip rate are effectively extracted from GPS time series.
The results suggest that six short term SSEs were embedded in the slow and steady long-term SSE during the time interval from the beginning of 2013 to the end of April 2015. We investigated the detected short term SSEs in more detail. The results shows: first, rapid SSEs occurred from October to December 2013 and from August to October 2014 which were accompanied by low frequency tremors. Then, a rapid SSE occurred from the beginning of January to February 2014around the Ise Bay. This SSE was also accompanied by low frequency tremors. Finally, another SSE was found in April 2015 and this SSE was also accompanied by low frequency tremors.
The results indicate that the maximum slip for the long term SSE from 1 January 2013 to 30 April 2015, was estimated to be about 6 cm and the large slip was located in nearly the same area as or slightly to the south of the previous event. This long term SSE is still continuing at the end of April 2015.

Crustal contraction of the Sado Ridge estimated from geologic structure, eastern margin of Japan Sea

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The amount of crustal shortening in the Sado Ridge, eastern margin of Japan Sea, was estimated from geologic structure. Many reverse faults have developed in the Sado Ridge under the W-E compressional stress during the last 3.5 million years. The faults were Miocene normal faults that have reactivated by inversion tectonics. The about 70 km wide ridge extends to NNE for about 250 km from the Sado Island and consists of many reverse faults accompanying asymmetric anticlines of 10 to 20 km wide. Assuming that these anticlines are fault-related folds above reverse faults that cut entire upper crust, it is possible to estimate amount of crustal shortening from the area of anticline on seismic profile that is product of thickness of the upper crust and horizontal slip of the fault.
This study based on seismic profiles acquired by the Geological Survey of Japan from 1989 to 1991. They are single-channel data, but they have enough quality to identify geologic structure of several hundreds meters below seafloor. The direction of seismic survey lines is 290° sub-parallel to the direction of contraction of the eastern margin of Japan Sea, and interval of the lines is about 3 km.
The onset of the reverse faulting is widely recognized by an unconformity marked by the change of reflection pattern from parallel to divergent below and above of the unconformity, which indicate that the ridge was nearly flat before the reverse faulting and uplift of anticline changed depositional patterns. I determined the geometry of anticline from the unconformity horizon on the seismic profiles and the area of anticline was measured assuming the unconformity was flat before folding. Some anticlines were truncated at their summits and a few may be composed of basement which has no internal structure. I determined fold geometry of anticlines from structure of underlying and surrounding sediments. Fifty seismic lines were analyzed to estimate crustal shortening.
The Sado Ridge is composed of several sub-parallel chains of anticlines. Although the area of anticline varies along the chain, the sum of the areas of anticlines along the WNW trending seismic lines crossing the entire Sado Ridge shows smaller variation. The crustal shortening of the ridge was roughly estimated to be 2 km or less assuming that the thickness of the upper crust is 15 km. This analysis suggests that the direction of crustal shortening is more westerly directed than 290°. I also discuss the problems and significance of estimation of crustal shortening using geological structure.

Keywords: eastern margin of Japan Sea, crustal contraction, fault-related fold

