

Spatio-temporal afterslip distribution of the 2011 Tohoku-Oki earthquake considering viscoelastic response

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1. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake with a moment magnitude (M_w) of 9.0 occurred at 5:46 (UTC) on March 11, 2011 along the boundary between the subducting Pacific Plate and the overlying plate. Since large earthquake are likely to produce stress concentrations in neighboring region along the plate boundary, the mainshock might have been trigger afterslip. It is very important to determine the detail of spatio-temporal distribution of afterslip, in order to understand the characteristic of friction relationship on the plate boundary. In this study, we estimate spatio-temporal afterslip distribution using visco-elastic Green's function (GF).

2. Method

We make GF using 3D finite element method (FEM) with a grid model for the Hokkaido and Tohoku regions. The model space and assumed subsurface structure for the 3D-FEM have a dimension of 2600 km (in the ESE direction) x 1500 km (in the NNE direction) x 400 km (depth) and typical subsurface structure consist of four sub-regions, i.e., upper crust, lower crust, upper mantle, and Pacific plate. The numbers of node and cell of 3D-FEM mesh are 3,205,950 and 3,121,200, respectively. For the calculation, we use the Pylith version 1.9.0, which is designed for simulating lithospheric deformation. In order to estimate the distribution of afterslip, we assume subfaults on the plate interface in and around the co-seismic slip zone of the 2011 Tohoku-Oki event. In inversion, we impose the smoothness constraint on the slip distribution. We estimate co-seismic and spatio-temporal distributions at the same time, considering visco-elastic response, derived from GEONET and seafloor observations.

3. Results and discussion

We obtain the co- and post-seismic slip distributions. The maximum slip of the 2011 event is about 60 m close to the Japan Trench. Estimated afterslip distribution is complementary to co-seismic slip distribution and also historical source regions. Amount of afterslip is about 2m, and the cumulative seismic moment is 8.06, considering visco-elastic response during 2.5 years after event. In case of only considering elastic response, amount of after slip is about 4m. There is no slip off Fukushima prefecture only considering visco-elastic response. And, our result can explain seabottom observations. i.e., Miyagi-Oki1 site move to west about 38 cm during 2 years after event. The effect of visco-elastic response is too large. In inversion for afterslip distribution from geodetic data, it must be consider to visco-elastic response due to relaxation in upper mantle.

Keywords: Afterslip, Visco-elastic response, FEM

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

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Large subsidence accompanied the 11 March 2011 Great East Japan Earthquake along the Pacific coast. GEONET data have indicated that the subsidence goes down westward (<http://www.gsi.go.jp/common/000059956.pdf>). In a summer field seminar by the Division of Earth and Planetary Material Science, Tohoku University, we made precise leveling survey for 10km on the second-order leveling route along the National Route 47 (from benchmark number 047-064 to 047-074; hereafter indicated as BM64, BM74 etc.) which locates along the east to west in Naruko area, Miyagi prefecture, to detect the vertical crustal deformation of this area. We performed the leveling twice (23-28 August, 2011 and 19-25 August, 2013) using bar-code leveling rods (Leica CPCL3) and an electronic digital level (Leica DNA03). By comparison with the data by Geospatial Information Authority of Japan in 2009, we acquired the change of difference in elevation at each benchmark against the westernmost BM64. We conducted round-trip survey between each benchmark and re-measured when the residual error did not meet the first-order leveling, except the segments between BM66 and BM68 in 2011 and between BM72 and BM74 in 2013 due to the fixed seminar schedule.

Contrary to our expectation before the leveling, we found all benchmarks subsided against BM64 and the degree of subsidence increases westward. At the 2011 leveling 5 months after the earthquake, benchmarks BM66, 68, 70, 72, and 74 subsided 13.0mm, 21.4mm, 81.7mm, 91.1mm and 113.9mm, respectively. This subsidence continued further with decreasing the amount, 8.5mm, 16.2mm, 23.7mm, 41.9mm and 46.2mm between 2011 and 2013, respectively. Obtained displacement pattern along the leveling survey between 2011 and 2013 is almost similar pattern with the 2009 and 2011 one.

Ozawa and Fujita (2013) and Takeda and Fukushima (2013) showed local depressions on some major volcanic areas in Tohoku region by In-SAR analysis. They explained the depressions by the east-west extension of hot and soft medium under the volcanoes. Our research route locates on one of that volcanic area and our leveling result is consistent with their previous studies. In contrast, their analysis just focused on the coseismic displacement. In our analysis, we found not only subsidence during the coseismic stage but also the subsidence in the postseismic stage. Particularly, it is worth noting that the subsidence increases remarkably between BM68 and BM70, which is inferred to cross the rim of Naruko caldera.

Acknowledgement

We appreciate Ryohei Kobayashi and Emi Hara who joined the leveling survey in 2011.

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

Postseismic gravity changes after the 2011 Tohoku earthquake recorded by superconducting gravimeters

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Continuous gravity monitoring by means of superconducting gravimeters is revealing significant effects of the 2011 Tohoku Earthquake on surface gravity in Japan. Two stations of superconducting gravimeters, Matsushiro and Kamioka, both in the main island of Japan (Honshu), are indicating gravity decreases at similar rates of approximately 10 microgal per year after the 2011 event, and this trend is still going on. Since Matsushiro and Kamioka are relatively far from the earthquake source region (epicentral distances being 420 km and 490 km, respectively), the postseismic crustal uplifts of the stations recorded by GPS are too small to account for the observed gravity decreases. Therefore, the observed gravity changes are likely to reflect ongoing changes in the density of the earth material, maybe associated with a viscoelastic flow of the asthenosphere. Data from Mizusawa, another SG station in Honshu, will also be presented in the paper.

Keywords: superconducting gravimeter, 2011 Tohoku earthquake, postseismic gravity changes, viscoelasticity

Pressure Source Model Inferred from Crustal Deformation Preceding Seismic Swarm in 2013 beneath Tarumae Volcano

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Tarumae-volcano is an active volcano with an altitude of 1,041 m located in the southwestern part of Hokkaido. In past 350 years, three major magmatic eruptions occurred, i.e. Plinian eruptions in 1667 and 1739 and dome forming eruption in 1909. Volcanic activity in recent years is restricted to gas emission or volcanic earthquake activity at the shallow part of the volcano. A spherical source model for inflation/deflation sequence is inferred at shallow depth beneath the summit dome by campaign GPS observations by the Meteorological Agency. No sign of crustal deformation is found at the deeper depth of the volcano by continuous GPS observation in a regional scale either by the Geographical Survey Institute nor the Meteorological Agency. Thus, until now, a crustal deformation which suggests fluid activity beneath the Tarumae-volcano at deeper depths had not been detected.

In July, 2013 swarm seismic activity started at the depths of between 2-5 km about 2 km to the west of summit dome. In addition a crustal deformation preceding the swarm was identified at several observation sites. The size of the change was at about 1 micro radian or micro strain level. Because the change appeared commonly at several stations around the volcano, it is highly likely that the strain and tilt change is resulting from a activity of a source at a depth beneath the volcano. A spherical inflation source was inferred from the observation data. The estimated position is at the m.s.l. depth of 4.2 km and about 1.3 km to the NNW of the summit horizontally with inflation volume of $3.4 \times 10^5 \text{ m}^3$.

Since the position and time of activation of the source are close to those of seismic activity, it is likely that there is some geodynamic relationship between swarm seismicity and crustal deformation. In our presentation we also discuss possible relationship between them.

Keywords: Crustal Deformation, Active Volcano, Swarm Earthquake, Tarumae Volcano

Campaign GPS for detection of the volcanic deformation on and around Mt.Meakan and Mt.Tokachi

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Mt. Meakan is an active volcano located in the eastern Hokkaido, Japan. It made phreatic eruptions in 1996, 1998, 2006 and 2008. Mt. Tokachi is one of the famous active volcanoes sits in the central Hokkaido. In the recent 100 years, three major magmatic eruptions took place in 1926, 1962 and 1988-1989.

In this presentation, we will discuss the results of the campaign GPS on and around Mt. Meakan and Mt. Tokachi. Each broad area GPS observation had begun at Mt. Meakan in 2006 and at Mt. Tokachi in 2007, respectively. The campaign GPS observations have made for several days to weeks in each year for Mt. Meakan at 8 sites, and that for Mt. Tokachi at 12 sites.

We used the data of our campaign observations after the 2008 eruption for Mt. Meakan and since 2007 for Mt. Tokachi. We also used the data of several sites operated by JMA (Japan Meteorological Agency) at the same time. Analyzing these data, annual movements at those points were estimated. These movements included deformations of the regional tectonic moving, and of the coseismic step of Tohoku-oki earthquake on March 11, 2011. For making corrections of these non-volcanic deformations, we used the continuous data of GEONET sites by Geospatial Information Authority of Japan (GSI) around the volcanoes. Using the GEONET data from 2007 to 2013, the regional tectonic and the seismic deformations were estimated by linear approximation in space. To elucidate the volcanic deformation, seasonal variations should be taken into consideration. The discussion about estimated volcanic deformation will be made, with the corrections about the regional deformation, the coseismic step and the after slip of 2011 Tohoku-oki earthquake, and the seasonal change.

Acknowledgements

In this study, JMA, Sapporo District Meteorological Observatory furnish their observation data to us. We would like to express our gratitude to them. Also, we used the data of GEONET sites of GSI with thanks.

Keywords: campaign GPS observation, volcanic crustal deformation, Mt. Tokachi, Mt. Meakan

Crustal deformation associated with the unrest of Zao Volcano

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Mt. Zao (1,841 m) is an active volcano located in northeastern Japan and having histories of phreatic or phreato-magmatic eruptions in the last 2 ka. Unrest of Zao volcano started in January, 2013 with a volcanic tremor (JMA, 2013) followed by activated seismicity mainly in the lower crust and very long-period seismic events (VLP) up to today. Since the number of volcanological observatories within a distance of 10 kilometers from the volcano was limited at the time of beginning of the unrest; two continuous GPS sites and two sites equipped with borehole seismometers and tiltmeters, Tohoku University has built up 4 sites with broadband seismometers, 5 sites with continuous GPS, 1 site with shallow borehole tiltmeter, and 2 sites with a Proton magnetometer.

Using the new broadband network, we detected some VLPs with dominant period of about 10 sec, and revealed the source of the VLPs is located at a depth range of 2-4 km beneath the crater lake, from where the recent eruptions occurred since ~600 years ago. There were, however, no significant surface phenomena such as steam explosion, ash effusion, and so on associated with the VLPs, except for precursory tilt signals about 5 minutes preceding a few major events.

We deployed dual-frequency GPS receivers at 5 new stations and the data are transmitted to the university using cellphone network for continuous observation (Demachi et al., 2011). The data are processed using the precise point positioning strategy (Zumberge et al., 1997) of GIPSY-OASIS II ver. 6.1.2 with IGS08 precise ephemerides and GMF mapping functions (GMF, Boehm et al., 2006). Since the wide area of northeastern Japan still suffers the long lasting postseismic deformation following the 2011 Tohoku-oki earthquake (M9.0), we try to extract volcanic deformation related to the unrest of the volcano using spatial and temporal filtering. Even though no distinct deformation has been recognized in the continuous GPS and tiltmeters at present, we may detect cm level variation of the shape of the mountain.

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Keywords: GPS, Ground Tilt, Volcanic deformation, Volcanic activity

The acceleration episode of the back-arc rifting in the Izu-Bonin Arc possibly triggered by a remote earthquake in 2004

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The Izu-Ogasawara (Bonin)-Mariana Island arc lies along the convergent boundary between the subducting Pacific plate (PA) and the overriding Philippine Sea plate (PH) in the western Pacific. Nishimura (2011) found that the back-arc rifting goes on behind the Izu arc by studying the horizontal velocities of GNSS stations on the Izu Islands. Here we show that this rifting has accelerated in 2004 using GNSS data at stations such as Aogashima, Hachijojima, Mikurajima, Shikinejima, and Nijima (we excluded stations in the Miyake Island because of the volcanic deformation).

The back-arc rifting behind the Izu islands can be seen as the increasing distance between stations in the Izu Islands (they are located to the east of the rifting axis) and stations located in the stable part of PH, e.g. Minami- and Kita-Daito islands. We found that their movement showed clear acceleration around the third quarter of 2004. Such an accelerated eastward movement could be interpreted not only as the acceleration of the back-arc rifting, but also as the trenchward movement of the arc due to a slow slip episode at the PH-PA boundary.

We first rule out the second possibility by constraining the onset time of the acceleration episode, and by correlating it with other inter-plate earthquakes in the PH-PA boundary. There was an inter-plate earthquake occurred on May 29, 2004 (M6.5) at the PA-PH boundary just to the south of the Boso-oki triple junction. However, the time series clearly lacked the jump which should mark the onset of the eastward slow movement. Moreover, the additional velocity vectors do not converge to the epicenter, and the onset time that minimizes the post-fit residual is significantly later than May. We therefore conclude that the accelerated eastward movement started in 2004 was not due to the afterslip of the interplate earthquake in May.

We found that the onset time coincides with the occurrence of the September 5, 2004, Kii-Hanto-oki, September 5, 2004, earthquake (M7.4), which occurred in the PH slab subducting at the Nankai Trough off the Kii Peninsula. We found that the accelerated movement vectors of these islands are almost parallel with each other, and perpendicular to the rift axis. We hypothesize that the seismic wave radiated from the epicenter of this earthquake dynamically triggered the acceleration of the back arc opening in the Izu Arc.

Keywords: GPS, GNSS, Izu-Bonin Arc, time series, back-arc opening, acceleration

Subsurface structure and slip pattern of the Median Tectonic Line, SW Japan inferred from GPS displacement rate field

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The Median Tectonic Line (MTL) is the longest arc-parallel fault system in southwest Japan. Its right-lateral strike-slip motion is originated from oblique subduction of the Philippine Sea plate at the Nankai Trough, separating the Nankai forearc sliver (the outer zone) from the inner zone of southwest Japan. The deformation of the forearc sliver is characterized by interseismic contraction in the direction of the plate convergence (NW-SE) and long-term westward block movement along the MTL. In addition the MTL itself has a potential to generate a large inland earthquake in the future. Therefore it is important to understand subsurface structure and current slip/locking pattern of the MTL fault plane.

From dense GPS campaign measurements along a traverse line across the MTL, we have made it clear that a transition zone of the relative motion between the outer and inner zones is located 20-30 km north of the surface trace of the MTL (Tabei et al., 2002). To interpret the transition zone, we used a northward-dipping MTL fault plane which was revealed by seismic reflection survey (Ito et al., 1996) and assumed that its upper part was locked and a stationary right-lateral slip was occurring at depth. However, the concept of a pure strike-slip on an inclined fault plane seems somewhat unrealistic. In addition linear distribution of earthquakes aligned 20-30 km north and parallel to the MTL seems inconsistent to the hypothesis of the dipping MTL fault plane because most of them show a right-lateral slip on a nearly vertical fault plane. Unfortunately station distribution of the nationwide continuous GPS network is rather sparse in the north of the MTL because of the existence of the Seto Inland Sea. In this area we have deployed supplementary three GPS stations and collected continuous data since November 2010.

We propose a kinematic model of the transition zone. The model consists of several vertical right-lateral faults in a hanging wall above the northward-dipping MTL fault plane, which are close and parallel to each other. Distributed slip deficits on this parallel fault system may block the relative motion between the outer and inner zones and act as a broad shear zone as a whole. In this study we assume four parallel faults with different widths and depths from surface. Integrated displacement field from relative block motion and slip deficits on these faults is consistent with that derived from a strike-slip on an inclined fault.

We check the effect of the 2011 Tohoku-Oki earthquake on the deformation field of southwest Japan. We compare two displacement rate fields before (Jan. 2006 - Dec. 2009) and after (Mar. 2011 - July 2013) the earthquake. After the earthquake, additional wide-area displacements of 1-4 cm/yr trending to the source region (extension) have been superposed on the original compressional deformation field due to the subduction of the Philippine Sea plate. No significant change has been recognized in the latter.

Keywords: Median Tectonic Line, Nankai Trough, GPS, Deformation

Continuous GPS observation in northern part of Nansei Islands

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GEONET, which is a nationwide GPS observation in Japan cover on all over Japan. However, there is a GEONET site in Toshima-mura which is located in northern part of Nansei Islands. This region is defined the boundary between Northern and Central part of Ryukyu arc (Nishimura et al., 2004). It is not clear that where is the boundary because there is almost no GPS site. Goto (2013) concluded that the great earthquake occurred in 1911 is the interpolate event in this region. We set up the continuous GPS in islands of this region due to observe crustal deformation in this region.

In Akuseki Island (AKSK), Takarajima (TAKR) and Kuchinoshima (KCHI), continuous GPS (CGPS) observation started in March 2007, July 2007 and September 2010, respectively. CGPS set up on Gajyajima (GJYA) and Ujishima (UJIS), where is a deserted island, in May 2009. CGPS in Yokoatejima (YKAT) started in September 2013. Data is recorded at CGPS sites. Electric power system at GJYA, UJIS and YKAT is composed of batteries and photovoltaic cells.

Bernese GPS Software ver. 5.0 are used with IGS precise ephemerides and IERS rotation parameters. We also estimated tropospheric delays every hour and their horizontal gradients every six hours.

The short-term repeatabilities are from 1.6 to 3.0 mm in horizontal component and from 6.5 to 7.9 mm in vertical components. These observation is expected to make contribution to resolve rigid movement and crustal deformation in this region.

The detection of crustal deformation associated with earthquake swarm in Tanzania observed by SAR

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The East Africa Rift Valley is one of the divergent plate boundaries can be seen on the land surface. The area undergoes middle-class earthquakes and eruptions due to the existing faults and volcanoes.

An earthquake swarm occurred in the Northern Tanzania in July 2007 including the largest earthquake with Mw5.9 and lasted for approximately two months. According to the Global CMT solution, eight $M > 5$ earthquakes occurred during the earthquake swarm and all of them were reported to be caused by normal fault. One week after the start of the swarm, an effusive eruption began at Mt. Oldoinyo Lengai located near the epicentral region, and a major ash eruption was observed by the time when swarm was terminated.

Biggs et al. (2009, 2013) also detected the crustal deformation associated with the earthquake swarm and Mt. Oldoinyo Lengai eruption, using mainly ENVISAT/ASAR C-band SAR data. In these interferograms, however, the ground displacements at some deforming areas were uncertain because of the difficult of phase-unwrapping. Also, these datasets were acquired only along the descending track, and the 3D deformation fields were unclear. Therefore, we used the L-band ALOS/PALSAR data obtained at both ascending and descending track to detect the detailed crustal deformation.

The purpose of this paper is to elucidate the mechanism of crustal deformation associated with the earthquake swarm in Tanzania in 2007 by interferometric synthetic aperture radar (InSAR).

By using InSAR data for ascending and descending track and the azimuth-offset data, we determined the 3D displacement. The results show a subsiding region along the NE-SW direction that are sandwiched by two horizontally deforming regions toward NW and SE directions. These spatial variation patterns are consistent with the expected direction, where the East Africa Rift Valley is expanding. In addition, the azimuth-offset data reveals slightly southward displacement in sediment area.

The ground at the subsiding region indicated ~62 cm subsidence and ~33 cm horizontal displacement toward SSE. The two-lobe pattern in eastern and western half each moved several centimeter upward and ~50 cm in NW-SE direction horizontally.

In order to describe the ground displacement in detail, we estimated a fault source model assuming slip distribution in a homogeneous elastic half-space. Considering the complexity of the fault geometry, we derive a non-planar fault source model with triangular dislocation elements. Based on the result captured by InSAR and the observed area is in tension field, we propose two fault segments. The model indicates dip-slip and strike-slip displacement with maximum slip of about 1 m and 75 cm at 2-4 km depth.

Derived slip distribution can well explain the spatial variation pattern acquired by InSAR. The amount of moment release inferred from the model (Geodetic Moment: GM) exceeds that of the earthquake swarm (Seismic Moment: SM), and the ratio (SM/GM) is 37.2 percent. The ratio indicates that significant aseismic crustal deformation contributes to GM.

Some interferograms also detected the crustal deformation associated with Mt. Oldoinyo Lengai eruption during the earthquake swarm. We will also discuss the relationship between the earthquake swarm and the volcanic eruption of Mt. Oldoinyo Lengai.

Keywords: InSAR, Crutal deformation, East Africa rift valley, Earthquake swarm, Continental techtonics, Tanzania

Coseismic Deformation Detected by SAR and Fault Source Modeling of the 2009 Cinchona Earthquake (Mw6.1), Costa Rica

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A shallow earthquake with magnitude 6.1 (Mw) occurred in Costa Rica, Central America, on 8 January 2009. This earthquake, called Cinchona earthquake, accompanied with many landslides and caused around 20 fatalities. In the proximity of epicenter, there is the Angel-Vara Blanca fault that has a strike NNW-SSE. Montero et al. (2009) inferred the fault as the earthquake source fault. After 4 days of the earthquake occurrence, Poas volcano located 6 km to the west of the epicenter erupted (Volcanic Explosivity Index 1) after a quiescence of one year. This volcano had remained dormant for a decade after 1996 and became active since 2006. As the 1st step to study the possible relationship between earthquake and volcanic eruption, we detected the coseismic deformation by using the ALOS/PALSAR data and created fault models to explain the data.

In this study, we used ascending (path 162, frame 190) and descending (path 465, frame 3410) data of ALOS/PALSAR. To correct for the topography effect, we used the digital elevation model of ASTER GDEM. We analyzed the SAR data with GAMMA software. In the interferogram processing, we removed the atmospheric noise. We calculated the Green's function by triangular dislocation elements using Meade (2007) scripts.

The detected interferogram indicated that the maximum coseismic LOS (Line of Sight) changes were 20cm for ascending and 22cm for descending track, respectively. We derived the fault source model that could explain the LOS changes by trial-and-error approach. The estimated strike/dip angle of the fault were 133/65, and the rake angle at the center of fault was -163 degree. The difference of fault parameter from Angel-Vara Blanca fault suggested that the previously unknown fault worked. We calculated the pressure change caused by fault movement. This indicated positive change (compression) under the Poas volcano.

Keywords: InSAR, Coseismic Deformation, Fault Source Model, Costa Rica

An acceleration event of creeping slip detected by precise leveling survey at the central part of the Longitudinal valle

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Precise levelling surveys were conducted across the central Longitudinal Valley Fault, eastern Taiwan, to understand the deformation of the transition zone between the stable fault creep area and the locked area, which maybe correspond to an asperity. In order to investigate the surface relationship between the fault creep area and the geological condition of the transition zone, we established levelling routes in the Yuli, and Chike-san areas. The Yuli area forms the geological boundary of the Lichi Melange Formation, which is composed of chaotic mudstones containing numerous exotic blocks of various sizes and lithologies. Along the Yuli route, located on the Lichi Melange, an uplift rate of 30 mm/yr was detected during the period 2010-2013, suggesting that aseismic fault creep might be continuing with long-term stability. Along the Chike-san route, located on no Lichi Melange, a vertical deformation rate of 8 mm/yr, 40mm/yr, and 20mm/yr were detected in the period 2010-2011, 2011-2012, and 2012-2013, respectively.

The creep slip distribution was estimated by using a two-dimensional single-fault model proposed at Chike-san in the period 2012-2013. Large slip rates were estimated at 4-5 km of the fault plane. At the previous periods 2010-2011 and 2011-2012, relatively large slip rates were estimated at two parts of the fault plane-one at a depth of about 1.5 km and another at a depth of 4-5 km-. We believe that the acceleration event of creeping slip was continued at the depth of 4-5 km in the period 2012-2013. The northern limit of the stable creep area may be the Yuli area. The episodic creep event occurred in the transition zone between the stable fault creep area and the asperity area. The boundary between the stable creep area and the episodic creep area is consistent with the geological boundary of the Lichi Melange Formation.

Keywords: Taiwan, Longitudinal valley fault, precise leveling survey, aseismic creep motion

Internal stress changes due to point dislocations in a spherical earth

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A simple and complete theory about internal deformations due to point dislocations in a homogeneous half-space was proposed by Okada (1992). This theory has been used by many researches to estimate Coulomb stress changes due to an earthquake and has contributed to understanding of seismology. Although a homogeneous half-space is a first approximation of the earth, global deformation like broad stress changes due to a great earthquake have to be calculated in a more realistic earth model, spherically symmetric earth model. Sun and Okubo (1993) succeeded in calculating surface displacements and gravity changes due to point dislocations in a spherically symmetric earth model. However, internal stress changes and displacements have never been calculated because there exist some difficulties to realize the calculation in spite of early proposal of a fundamental method (Takeuchi and Saito, 1972). In this research, we propose a strategy to realize the calculation of internal deformations and present some computational results.

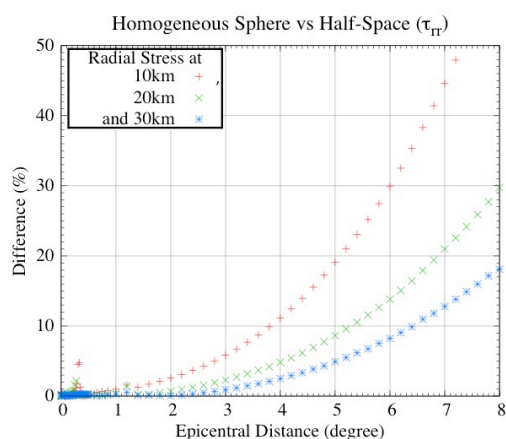
We shall

- i) outline the strategy to calculate internal deformations,
- ii) compare the stress changes in a homogeneous sphere with those in a half-space which were already solved and
- iii) show the results in a stratified earth model such as PREM.

Our study shows that significant difference between a homogeneous sphere and a half-space model occurs when epicentral distance exceeds several hundreds kilometers. For example, epicentral distances at which difference of radial stress changes in two models reach 10% are 4, 5 and 6.5 degrees at observation depth at 10, 20 and 30, respectively (Figure). Angular distance of 4 degrees, which is 400km, roughly equals the length of fault that is thought to have slipped in the 2011 Tohoku-Oki earthquake.

Figure. Difference of radial normal stress changes due to a vertical-strike slip at depth of 32km in two models, a homogeneous sphere and a half-space. The horizontal axis is epicentral distance and vertical axis is difference between the two models in percentage. Red, green and blue points indicate observation depth of 10, 20 and 30km, respectively.

Keywords: internal stress change, spherically symmetric earth, point dislocation, stratification



Continuous measurements of ocean bottom crustal movements based on GPS-acoustic system using GPS buoy

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We report the results of experiments of continuous measurements of ocean bottom crustal movements using GPS buoy and acoustic system.

We have developed a GPS buoy system for the early detection of tsunami. The system uses a buoy that is freely floating on the sea, tied to the sea bottom using an anchor, equipped with a GPS sensor at the top of the buoy. The system enables us to estimate the position of the buoy in a few centimeter accuracy.

On the other hand, Spiess (1985) and other researchers have developed the GPS-acoustic system for estimating the ocean bottom position in sub-decimeter accuracy. However, these systems have used owned or chartered vessels to measure the position of ocean surface, so that the measurements have been only intermittent. After the 2011 Tohoku-oki earthquake of Mw9.0, it has been recognized that continuous monitoring of ocean bottom crustal deformation is very important. Thus, we got an idea in that the GPS buoy could be used for the continuous monitoring of the ocean bottom crustal movements, if an acoustic system is equipped at the GPS buoy.

Based on this idea, we started experiments using our GPS buoy, which is located off Muroto Peninsula, western Japan, in the year of 2013. After a preliminary experiment in March 2013, we made an experimental observation from August to October of 2013. Three transponders were placed around the buoy and the equipment of sound sender/receiver at the side surface of the buoy. The water depth of the site is about 700meter and the ocean bottom transponders are placed so that the distances among these are in the same scale. We will report the results including noise characteristics of data, daily repeatability of estimated ocean bottom position, effects of swinging buoy, etc.

Currently, 15 GPS buoys have been established around the Japanese coasts. Augmentations of the acoustic system in these GPS buoy network will provide a powerful tool of monitoring ocean bottom crustal movements as well as tsunamis. Further requirements to GPS buoys are to be placed farther offshore, say, more than 100km from the coast. Recent developments of the GPS buoy system, including a newly developed algorithm, PPP-AR (precise point positioning with ambiguity resolution), clarified this requirements. However, still another problem of how data at the buoy placed far offshore is transmitted to land in real-time manner is still to be solved. For such problem of a newly designed high capacity data transmission system using a dedicated satellite system will be necessary. Our current experiment will provide an important data for designing a specification of such satellite system.

Spiess, IEEE Trans. Geosci. Remote Sens., 23, 502-510, 1985

Movement of a fault arised by a pumping or a spring water and its understanding by poroelasticity -a case of NNW fault-

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¹TRIES, ADEP

Tono Research Institute of Earthquake Science (TRIES) has developed a borehole stress meter for continuous observation and multi-component borehole instruments. At the present time about 15 borehole stations are in operation. We have investigated crustal movements and behavior of underground water by using data obtained from borehole observations. The depth of the deepest borehole is 1030 m.

Near TRIES, JAEA (Japan Atomic Energy Agency) is constructing deep boreholes with diameters of 4m and 6.5m. And depth is about 500m at the present time. The boreholes are 40m apart and connected by stages. NNW fault is running beside the 6.5m borehole. We are investigating a relationship between water flow and geophysical observations by using experiments of pumping water and spring water.

The main results obtained are as follows:

1. Water level of TGR350 borehole station decreases by pumping water and spring water. Data of the strain meters installed at 350m depth indicate right lateral movements of NNW fault.
2. Data of the strain meters installed at 350m depth indicate left lateral movements of NNW fault in case of recovery of water level.
3. Strain meters installed shallower depth (165m) and extensometers installed in sedimentary layer do not indicate such fault movements.
4. We have considered a mechanism explaining the phenomena by using poroelastic understanding.

We will present the details of observations and analyses.

Keywords: Deep borehole observation, Fault movement by spring and pumping water, Groundwater flow, Understand by poroelasticity, Continuously observable stressmeter

Construction of Syobasama crustal activity observatory ?Installation of Ishii-type borehole stressmeter?

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Large changes in the pore pressure in Toki granite have produced by the excavation of underground facilities of Mizunami Underground Research Laboratory (MIU) and drilling well for hydraulic tests in MIU (e.g. Asai and Ishii, JpGU2013). We have observed remarkable stress/strain/tilt variations associated with the pore pressure changes at borehole observation site TRIES, STG300 (on the north-east side of the fault), Togari(TGR350/TGR165), STG100, STG200 (south-west side), respectively within 500m of the MIU.

In this area the NNW trending sub-vertical (normal) fault is exists (e.g. JNC, 2003 and 2004). Pore pressure changes occurs in the south-west side of the fault, its impact were observed in water level/pressure record of the same side, and were also observed in stress, strain and tilt record. On the other hand, its impact were not seen in the water level/pressure record of the north-east side of the fault, but its impact were observed on stress, strain and tilt record. Pore pressure change occurs in the north-east side of the fault are similar to those of the south-east side. This observation results indicate that fault has impermeability and elastic deformation of the rock caused by pore pressure change extends over the fault.

In order to clarify the relationship of groundwater level changes to crustal strain changes at Syobasama observation site which is located approximately 1km northwest of MIU, Tono Research Institute of Earthquake Science has constructed the new borehole depth of 110 m and installation of Ishii-type borehole stress meters is scheduled in February 2014. We will present the details of construction of Syobasama observatory, and result of continuous stress observation with groundwater records.

Keywords: Pore pressure change, Elastic deformation, Mizunami Underground Research Laboratory, Ishii-type borehole stress meter

Post-seismic crustal movements of the 11 April Mw6.6 Fukushima Hamadori earthquake based on GPS observations

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Tohoku earthquake on March 11, 2011 (Mw9.0) was accompanied by a vigorous aftershock activity. One of the aftershocks occurred on April 11, 2011, nearby Iwaki city, Fukushima Prefecture, and was called as Fukushima-Hamadori earthquake (Mw6.6; Depth=5km). The focal mechanism of the earthquake was a normal fault. Co-seismic crustal movements due to the earthquake observed by GPS observation was amounted to about 30cm to northeast direction at Iwaki site.

Crustal deformations associated with the Fukushima-Hamadori earthquake is obtained by InSAR and the data were used to construct detailed fault slip models by the previous studies (Kobayashi et al.,2013 : Fukushima et al.,2013). However, it has not been possible to measure the postseismic deformations using the SAR because the ALOS satellite has terminated its operation in immediately after the Fukushima-Hamadori earthquake. Thus, the postseismic crustal movements has been observed only by the GPS observations. Therefore, we aim to elucidate the mechanism of postseismic deformations due to the Fukushima-Hamadori earthquake using the GPS data in this study.

In this study, it was assumed that postseismic crustal deformations were caused by a slip in the vicinity of the fault. We used earthquake fault geometries employed by previous studies (Kobayashi et al.,2013 : Fukushima et al.,2013). As the GPS data is including large postseismic displacements due to the main shock since the March 11, first, we removed the postseismic transient displacements from GPS data using a postseismic slip model of the main shock (Fukuda et al., 2013). The obtained residual displacements after April 11, 2011, are considered as postseismic displacements due to the Fukushima-Hamadori earthquake. We, then, estimated slip distribution on the fault plane based on the residual displacement field. We will discuss estimated results in our presentation.

Coseismic slip distribution for the 2011 Tohoku-Oki earthquake with topographic corrections

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Seismological study (Ide et al., 2011) revealed that the rupture of the 2011 Tohoku-Oki earthquake extended to the Japan Trench (i.e. free surface). Since the depth of the trench is about 8km, it is not appropriate to use green functions for elastic half-space media as given by e.g., Okada (1992). When we employ green functions for the half-space, it is not possible to satisfy the following two conditions simultaneously; (1) the updip limit of the rupture is ~8km deeper than the ground surface, and (2) the rupture extends to the free surface (i.e. the trench). If the condition (1) is satisfied, the rupture extends to ~8km at depth, not to the free surface. On the other hand, if the condition (2) is satisfied, the depth of the trench must match to the ground surface. The maximum discrepancy in between predicted ground displacements for the condition (1) and (2) is 5% in horizontal, and 15% in vertical component. Thus, it may be important to take the topography into account in green functions.

In this study we applied the topographic correction on green functions as proposed by Williams and Wadge (2000). Segall (2010) suggests that this method is applicable to approximately incorporate the earth sphericity into green function for observation sites within about 600km from the dislocation. Combining those two corrections, we are able to calculate corrected green functions for spherical earth with topography. Although this method gives only approximate green functions, it helps us to investigate the dependence of green functions on topography and fault geometry.

Then we use the corrected green functions for the inversion of coseismic slip distribution for the 2011 Tohoku-Oki earthquake. In the inversion we use the following data set: GEONET F3 solutions obtained by the Geospatial Information Authority of Japan (GSI), the ocean bottom deformation data by the Japan Coast Guard (Sato et al., 2011), and that of Tohoku University (Kido et al., 2011; Ito et al., 2011). Then the inversion result is compared with the half-space solutions.

Keywords: crustal deformation, the 2011 Tohoku-Oki earthquake, topography, sphere

Secular change of permeability estimated by using the variations of groundwater discharge

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Secular change of permeability causes the variation of the atmospheric pressure admittance of groundwater discharge. We estimated the permeability of the surrounding crust by using the groundwater discharge observed at Rokko-Takao station during 12 years from 2001 to 2012. The estimated secular change of permeability contained the short term variations for about a year as well as the gradual decrease. It is considered that the gradual decrease of permeability was caused by the closure of the cracks, which were opened in the 1995 Hyogoken Nanbu earthquake, due to the accumulation of mud and the crustal stress. On the other hand, the short term variations of permeability suggest the temporary re-open of the cracks due to the earthquake ground motions.

The Rokko-Takao station is located in Kobe, the southern Hyogo prefecture, and passes through the fracture zone of Manpukuji fault. At this station, the significant increase of groundwater discharge was observed just after the 1995 Hyogoken Nanbu earthquake (Fujimori et al., 1995). This suggested that the many cracks were opened in the fracture zone around the station by the ground motion of the earthquake. Mukai and Otsuka (2009) estimated the elastic properties by using the tidal strains observed at the station and reported that the Young's modulus of the surrounding crust showed the secular increase. This suggested that a part of cracks were closed by the crustal stress and the accumulation of mud and the strength of the fracture zone had been recovering.

Mukai and Otsuka (2013) estimated the variations of permeability due to the 2011 Tohoku earthquake by using the atmospheric pressure admittances of the groundwater discharge observed at the station under the assumption of one-dimensional model about groundwater migration. The permeability just after the earthquake increased by about 1.9 times just before the earthquake and decreased to the level about 1.3 times just before the earthquake in 10 months. This suggested that even the small ground motions due to the teleseismic waves could cause the outflow of the mud and the temporary re-open of the cracks in the fracture zone.

In this study, we estimated the secular change of permeability around the station during 12 years from 2001 to 2012 by using the procedure of Mukai and Otsuka (2013). The permeability estimated by using the atmospheric pressure admittances of the groundwater discharge showed the secular decrease by about 50% in 12 years. This result agrees to the secular increase of Young's modulus estimated by using the tidal strain and is considered that the gradual decrease of permeability was caused by the recovering of the fracture zone, in which the cracks were opened in the 1995 Hyogoken Nanbu earthquake.

Keywords: fracture zone, permeability, groundwater discharge, strain change

Vertical crustal deformation in Boso Peninsula from 1966 to 2001 deduced from leveling and sea level data

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Leveling data and sea level data for the period from 1966 to 2001 in Boso Peninsula, Japan, were investigated to characterize unsteady vertical deformation. We estimated the steady vertical deformation rate at each GEONET GNSS station using the daily coordinates for the periods from January 1997 to January 2011 avoiding the period of the large earthquakes.

First-order leveling surveys have been conducted repeatedly every one or several years since 1966 in Boso Peninsula. We determined crustal displacements by comparing leveling data from successive surveys. We subtracted subduction-related steady component derived by the GNSS from the distribution of vertical crustal displacements during periods between leveling surveys. If any episodic events have not occurred, they should show little spatial variation around zero vertical displacement. Unsteady vertical deformation was not seen in the period from 1966 to 2001 except the land subsidence by pumping industrial water and natural gas brine.

Keywords: Boso Peninsula, crustal deformation, leveling, sea level

2014 Boso slow slip

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Introduction

The GPS network detected transient crustal deformation on the Boso peninsula in 1996, 2002, 2007, and 2011. The detected transient displacements subsided for approximately 10 days. Rupture process and slip area are similar among the past four Boso SSE. The recurrence intervals of Boso SSE are 6.4, 4.9, 4.2 years from 1996. Under this circumstance, the anticipated slow slip event started from January 1 2014. This recurrence interval of 2.2 years is the shortest one compared with the previous 4 slow slip events. In this research, we estimate spatio-temporal evolution of the 2014 Boso slow slip and compare it with those in 1996, 2002, 2007, 2011.

Data and analytical procedure

Trend and annual components which are estimated for the period between 2009 and 2011 are removed from the raw time series. The detrended crustal deformation in 2014 shows southeastward movements with 1 cm maximum movement in the Pacific coastal area.

We employed time dependent inversion to the detrended crustal deformation associated with the 2014 Boso SSEs. We used EW, NS, and UD components of crustal deformation at approximately 40 GPS sites relative to Yasato station. The plate geometry of the upper surface of the Philippine Sea plate is based on Nakajima and Hasegawa [2006]. The fault geometry is composed on the B-spline and slip on the fault is also composed of superposition of B-spline function. As a boundary condition, we set 0 slip on the edge of the fault geometry.

Results and Discussion

The results show that the slow slip started offshore of the Boso peninsula and expanded to the south over time. The estimated moment magnitudes are 6.4, while those area 6.4 in 1996, 6.5 in 2002, 6.5 in 2007 and 6.6 in 2011. The 2014 Boso SSE ruptured an area similar to those of the four Boso SSEs. The recurrence interval is 6.4 year from 1996 to 2002 events, 4.9 years from 2002 to 2007 events, 4.3 year from 2007 to 2011, and 2.2 years from 2011 to 2014 events. The five events do not seem to be slip predictable nor time predictable. Though the 2011 event shows the largest magnitude among four cases, recurrence interval from 2007 event is the shortest. We cannot rule out a possibility that the Tohoku earthquake may have affected the occurrence of the 2011 event. In fact, dCFF increased near the rupture area of the Boso peninsula from the Tohoku earthquake [Hirose et al. 2012]. However, it remains unclear the reason why recurrence interval change drastically from 4.2 to 2.2 years for the 2011 and 2014 events, since dCFF does not change so much from 2011 and 2014. Another interpretation of shortening of recurrence interval is based on a scenario proposed by several simulation studies in which recurrence interval of slow slip events become shorter as occurrence of large earthquake nears. If this is the case, it is quite important to monitor crustal deformation on and around the Boso peninsula..

Keywords: Boso peninsula, slow slip

Estimation of frictional parameters in afterslip areas by assimilating GPS data :The 2003 Tokachi-oki earthquake

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Seismological and geodetic observations have revealed that various aspects of fault slips are determined by frictional properties on the interface. Kano et al. (2013) developed an adjoint data assimilation method to estimate frictional parameters from synthetic in-situ slip velocity data and found by numerical experiments that all frictional parameters are constrained if both acceleration and deceleration phases are observed. Additionally, we found that synthetic surface displacement data also have the ability to constrain frictional parameters in the areas where slip is well resolved. Following their study, we then applied the method to an actual case of the 2003 Tokachi-oki earthquake. Given reasonable initial conditions of simulation variables, estimated frictional parameters are well constrained if two conditions above are satisfied. Our results imply that the adjoint method we developed is useful to investigate and understand fault frictional properties.

Keywords: afterslip, adjoint method, frictional parameters, GPS, earthquake cycle

Crustal deformation of the northeastern margin of the Izu Collision Zone inferred from GPS observations

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Izu Collision Zone is characterized by the collision between Izu Peninsula and Tanzawa Mountains, and Philippine Sea Plate also subducts beside this zone. Because of these complicated plate geometries, a number of historical earthquakes occurred in the northeastern margin of this zone. Additionally, there are a lot of active faults in the marginal area of the collision zone.

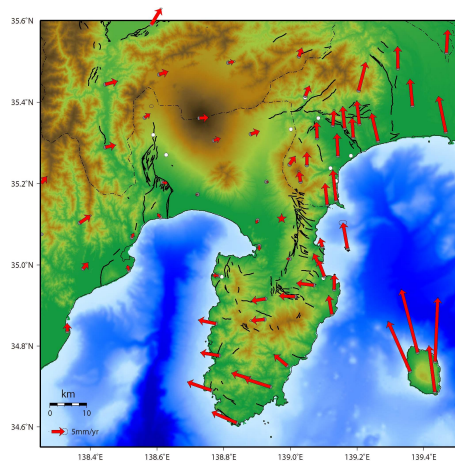
It is important to describe the steady state of crustal deformation in the Izu Collision Zone, in order to clarify mechanisms of earthquakes occurring in this area. In this study, we examined crustal deformation of the northeastern margin of Izu Collision Zone by using the datasets of GEONET sites (coordinate F3) and our original GPS sites.

Based on the displacement velocity vector diagram and profile, we can point out the following characteristics of crustal deformation there.

- 1) Remarkable northward crustal displacement vectors were observed in the eastern area of the Kita-Izu fault zone.
- 2) A shear zone with North-South trend was detected in the area between Kita-Izu fault zone and Ashigara Plain. Width of its zone was estimated about 15-20 km. Average shear strain rate in this zone was about 0.47 micro-strain per year.
- 3) Such remarkable crustal displacement vectors were not observed in the western area of the Kita-Izu fault zone.

This shear zone may be a transition zone between the collision and the subduction blocks on the Philippine Sea Plate, caused by the displacement gap between the blocks.

Keywords: GPS, crustal deformation, Izu Collision Zone, Kita-Izu fault zone



The wind velocity correction of the precipitation to use for the rainfall correction of the volumetric strainmeter

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The rainfall correction of the volumetric strainmeter has the sensitivity that can judge quality of the precipitation data.(Kimura et al., 2013) In the observation of the rain gauge, it is well known that a capture rate of the rainfall decline at the time of a strong wind. We try the rainfall correction of the volumetric strainmeter in consideration of wind velocity dependence. As a result, the strainmeters at the slope of the big mountain or near the river where had a long basin area is improved the rainfall correction. This is not influence of the capture rate of the rain gauges, it is caused by the fact that altitude dependence of the precipitation is remarkable as a strong wind.

For the rainfall correction of the crustal movement data such as the volumetric strainmeter, it is necessary to consider it about the rainfall at high altitudes in addition to the precipitation around the observation station.

Keywords: strainmeter, rainfall correction, wind velocity, altitude dependence of the precipitation

The change except the sudden contraction of the Higashiizu staraimeter with the seismic activity east off Izu Peninsula

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The sudden contraction strain change of the Higashiizu staraimeter with the seismic activity east off Izu Peninsula is well known. These changes were clear for anyone, but the Higashiizu staraimeter couldn't detect the long-term change that Murakami(2006) pointed out by the GNSS data until now. However we became able to remove the seasonal change by the rainfall from the strainmeter data by using the rainfall correction(Kimura et al., submitted). After reviewing the Higashiizu strainmeter data using the rainfall correction, this data detect the interesting change with the seismic activity east off Izu Peninsula.

Keywords: Strainmeter, seismic activity east off Izu Peninsula, Higashiizu

Characteristic strain distribution following the 2011 Tohoku earthquake based on the kinematic PPP analysis

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The 2011 off the Pacific coast of Tohoku Earthquake (March 11, 2011, M 9.0) generated widespread coseismic deformation. The slip on the plate boundary is larger than the 10 m in widely (e.g. [1]). Ohzono et al [2] found inhomogeneous strain distribution caused by the coseismic step of the 2011 Tohoku earthquake. They extracted the residual strain distribution, which is estimated by comparison between the expected coseismic displacement by a simple rectangular faults model and the observed coseismic displacement in the Tohoku area. Ozawa and Fujita [3] found the local deformation around the Akita-Komagatake, Kurikoma, Zao, Azuma, and Nasu volcanoes caused by the 2011 Tohoku earthquake based on the ALOS/PALSAR and GPS data. They suggested that the coseismic extensional deformation concentrates in the soft medium under a volcano and that this deformation has caused local deformation with subsidence based on the FEM modeling. These previous studies, however, used the daily coordinates time series of the GPS observation. Thus, these previous studies result might be contained early postseismic displacement following the 2011 Tohoku earthquake. Based on these backgrounds, we tried to extract the pure coseismic deformation by the kinematic Precise Point Positioning (kPPP) approach.

We estimated every 1 seconds coordinates time series of the 1,208 GEONET by the GIPSY-OASIS II software version 6.1.2. We defined the "pure" coseismic displacement, which is coordinate difference between just before the origin time and 600 seconds after the event. We averaged from 500 to 700 seconds after the event for eliminating short-term fluctuation of the time series. Based on the estimated "pure" coseismic displacement, we estimate the dilatation strain distribution by method of the [4]. We also estimated strain distribution in the early time period after the 2011 Tohoku earthquake, which estimated coordinate difference between coseismic displacement by the daily coordinate (e.g. difference between 10 to 12th March, 2011) and "pure" coseismic displacement by the kPPP analysis.

As a result, we found the characteristic local expansion in and around the Mt. Gassan, which located in Yamagata prefecture. We also found the characteristic contraction in and around Mt. Zao even though this obtained strain amount is smaller than the noise level determined by the kPPP time series. We also estimated strain distribution of early postseismic between mainshock and 15th March for the understanding the spatiotemporal development of strain distribution. The area of the expansion is clearly larger than the 12th March in and around the Mt. Gassan. Furthermore, the contraction area around the Mt. Zao clearly changed to expansion between just after the mainshock and 15th March.

In the presentation, we will discuss more detail characteristics and its interpretation of the obtained strain distribution.

[1] Inuma et al., (JGR, 2012), [2] Ohzono et al., (EPS, 2012), [3] Ozawa and Fujita, (JGR, 2013), [4] Shen et al., (JGR, 1996)

Keywords: strain, 2011 Tohoku earthquake, postseismic deformation, kinematic PPP

Convergence of the Philippine Sea Plate in Mindanao, the Philippines

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Tectonics of the Philippines Archipelago is characterized by westward subduction of the Philippine Sea plate at the Philippine Trench in the east (5.8 - 7.0 cm/yr), eastward subduction of the Sunda plate at the Manila Trench in the west (3.3 - 3.6 cm/yr), and left-lateral strike-slip movement of the Philippine fault inland. Under the SATREPS project "Enhancement of earthquake and volcano monitoring and effective utilization of disaster mitigation information in the Philippines" we have conducted yearly GPS campaign measurements in the eastern part of Mindanao since March 2010. The main purpose of the observation is to make clear the plate locking distribution at the Philippine Trench and slip/locking pattern of the Philippine fault in order to estimate earthquake generation potential in Mindanao.

We occupied 15 sites in the eastern Mindanao and collected continuous data for successive three to six days on March 2010-2013. Collected data were processed with Bernese software ver.5.0 together with the data from global IGS station (PIMO near Manila) to obtain coordinates and displacement rates based on ITRF2008. The displacement rates were then converted to those with respect to the Sunda plate. Moreover we used previous displacement rate data obtained in the central and western Mindanao from the 1997-2003 campaign measurements to cover the whole of Mindanao.

The resulted displacement rate field shows that west-northwest motions are dominant due to the convergence of the Philippine Sea plate from the east but their spatial decay with increasing distance from the trench is not significant. Even the full locking of the Philippine Trench plate interface down to the depth of 80 km can explain only 29 percent of the observed displacement rate at the maximum. Thus we need to introduce remarkable rigid block rotations to interpret the deformation pattern of Mindanao. As a result of the estimate of pole position and angular velocity of the block rotation, deformation field of Mindanao cannot be reproduced by a rotation of single block. Considering the Philippine fault as a block boundary, it is natural to introduce multiple blocks into Mindanao. Unfortunately current station coverage and density are not enough to resolve elastic deformation due to plate locking at the trench and rigid motions due to multiple block rotations.

Keywords: Philippine Trench, Philippine fault, GPS observation, Mindanao

Slip deficit rate distribution and its temporal changes along the Japan islands

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The Japan islands are located along several plate boundaries, where the oceanic plates are subducting beneath the continental plates. Due to this subduction, slip deficits are being generated and strain is being accumulated in coupled zones of the plate boundary so that many large earthquakes have occurred. Therefore, in order to reveal the generation mechanism of large earthquakes at the plate boundaries, it is necessary to clarify slip deficit rate distributions. In addition, as seen in long-term slow slip events, there are significant temporal changes in the slip deficit rate distributions. In this study, we determined the slip deficit rate distribution along the whole Japan islands for each year from 1996 to 2010 (the observation period of GEONET operated by GSI before the 2011 Tohoku earthquake) using the inversion method, and compared each other to investigate their temporal changes.

For calculating the deformation fields in Japan, we used the daily coordinates of F3 solutions. We obtained daily time series data considering the movements of the continental plates against reference frame and removing the offsets and postseismic effects due to nearby earthquakes. We then derived horizontal rate fields in Japan for each year by least-squares fittings. For reflecting the geometry of the plate boundaries, we used the plate model (Baba et al., 2005) incorporated in JIVSM (Koketsu et al., 2012). The Green's functions were calculated using the frequency-wavenumber method (Zhu and Rivera, 2002). We performed slip deficit inversions using the method of Yoshida et al. (1996).

The slip deficit rate distributions derived from the inversions were consistent with the previous study and the plate convergence rates. In addition, known long-term slow slip events were found in the temporal changes of the slip deficit rate distributions. Furthermore, we can see the temporal changes in the Hokkaido and Kanto regions, which suggest variations of plate coupling in these regions. The zones of large slip deficit rate in the distributions look corresponding to the source regions of past megathrust earthquakes. These correspondences are significant not only in Earth science but also in seismic hazard assessments.

Acknowledgement: We would like to thank Geographical Survey Institute for geodetic data recorded by GEONET.

Keywords: the Japan islands, crustal deformation, GPS, slip deficit, megathrust earthquake