SCG74-01 Room:IC Time:May 24 13:45-14:00

Coseismic displacement of the 2011 Tohoku-Oki earthquake detected by repeated multi-narrow beam bathymetric surveys

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After the 11 March 2011 Tohoku-Oki earthquake, we carried out bathymetric surveys using the R/V Kairei in the rupture zone across the Japan Trench. Some survey tracks were aligned along the tracks obtained before the earthquake, and we analyzed the difference in bathymetry before and after the earthquake. Although the results may incorporate errors of several meters in vertical displacement and ~20 m in horizontal displacement, the extraordinary coseismic displacement caused by the 2011 earthquake was detected by the bathymetric surveys.

Off the coast of Miyagi in the Tohoku district, the R/V Kairei surveys had been conducted in 1999 and 2004 [e.g. Tsuru et al., 2002 JGR; Ito et al., 2005 GRL; Miura et al., 2005 Tectonophys.]. For analysis, we used only the data obtained by beams within a 45^o swath width (3-6 km) because these inner beam soundings have higher accuracy and less effects of errors in water column sound velocity. Direct comparisons of absolute values of soundings were hampered by the differences of sound velocities used to calculate the depths and by the uncertainty of ship position. The apparent offsets were examined on the seaward side, because the seaward was thought to have suffered little change from the earthquake. For the 38^{o}N track, there were large relative differences landward extended up to the trench axis (~144^{o}00'E, water depth ~7600 m), suggesting the earthquake fault rupture reached the trench axis. The 2011 seafloor is shallower throughout the landward side. Notably, on the outermost landward slope, the 40 km wide area between the slope break (water depth 3700 m) and the trench axis, the difference between the 1999, 2004, and 2011 data shows the seafloor is ~11-16 m shallower on average. Furthermore, locally upward and downward changes in seafloor elevation of +/-50 m are evident at the axial seafloor. These changes are likely due to seafloor deformation at the place of the plate boundary fault reaching the seafloor. Comparison of the 1999 and 2004 data obtained before the 2011 earthquake indicated no clear difference between the two sides of the trench axis.

The observed seafloor elevation change on the outermost landward slope corresponds to a sum of vertical displacement and additional uplift for the sloping seafloor due to horizontal displacement. We estimated the horizontal displacement by calculating the offset distance to maximize the cross-correlation of bathymetry. The estimated displacement is ~50 m in the east-southeast toward the trench. After restoring the horizontal displacement, the average elevation change became ~7-10 m in comparison between the 1999, 2004, and 2011 data. We interpret these to represent vertical displacement, from the fault motion along the subducting plate and uplift from other unknown processes such as inelastic deformation.

For the 38.5^{o}N track, bathymetric data comparison shows the same trend, and there are relative differences landward extended up to the trench axis (~144^{o}05'E). Though, change in seafloor elevation along this track is smaller than that along the 38^{o}N track.

Combined with results of coseismic displacements determined at GPS/acoustic seafloor geodetic stations and other ocean-bottom instruments deployed off Miyagi [Ito et al., 2011 GRL; Kido et al., 2011 GRL; Sato et al., 2011 Science], our study demonstrates the coseismic displacement increasing toward the trench. This large horizontal displacement and the steeply sloping seafloor on the outermost landward slope having an average inclination of 5^o produced large additional uplift by ~4-6 m in addition to the vertical displacement. This uplift was likely an important factor contributing to the generation of the massive pulsating pattern of tsunami waves observed by cabled seafloor pressure gauge [e.g. Maeda et al., 2011 EPS].

The 2011 survey, part of the program launched following the earthquake, was supported by a Grant-in-Aid for Special Purposes of the MEXT and a contribution from JAMSTEC.

Keywords: 2011 Tohoku-Oki earthquake, multi-narrow beam bathymetry, coseismic displacement, tsunami, sub-marine landslide

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SCG74-02 Room:IC Time:May 24 14:00-14:15

Seafloor movements associated with the 2011 Tohoku Earthquake detected by GPS/acoustic geodetic observation

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The Hydrographic and Oceanographic Department, Japan Coast Guard, have been developing precise seafloor positioning systems using the GPS/acoustic combination technique under technical cooperation with the Institute of Industrial Science, the University of Tokyo and carrying out campaign observations along the major trenches in the Pacific Ocean, such as the Japan Trench and the Nankai Trough. The primary purpose of these observations is to detect and monitor the crustal deformation caused by the subduction of the oceanic plate near the plate boundary where huge earthquakes repeatedly occur.

On 11 March 2011, a large interplate earthquake [Mw = 9.0] occurred at the plate boundary off Miyagi Prefecture, northeastern Japan. Various studies have been under way to understand the mechanism of occurrence of this earthquake. For example, the Geospatial Information Authority of Japan (GSI) has reported coseismic displacements on land, on the basis of the dense GPS network. The largest displacement has been detected at the Oshika peninsula, amounting to about 5 m toward ESE and about 1 m downward.

Because the Oshika peninsula is located about 130 km away from the epicenter of the earthquake, it is preferable to measure crustal movements closer to the focal regions, that is, on the seafloor, to better constrain the focal mechanism of the event.

In order to monitor crustal movements offshore, we have been carrying out seafloor geodetic observations. Five sea-floor reference points were installed off the Tohoku region between 2000 and 2004 with campaign observations carried out three times a year on average. After the event, we conducted observations at these sites. Comparison between before and after the event yielded coseismic displacements of 5 to 24 m toward ESE and ?0.8 to 3 m upward. In particular, at reference point near the epicenter, we detected a huge coseismic displacement of about 24 m toward ESE and about 3 m upward. This is more than four times larger than that detected on land.

These results suggest that slip on the plate boundary near the trench exceeded the 20- to 30-m level estimated as a maximum by the terrestrial data, because slip on the plate boundary should be much larger than displacement of the sea floor.

With only five observation sites, we may not be able to constrain the detailed feature of focal mechanism, but we believe that the coseismic displacements obtained offshore in this study will provide far better constraints than only the terrestrial data in inferring a fault model for this event.

Keywords: Seafloor geodetic observation, the 2011 Tohoku earthquake

SCG74-03 Room:IC Time:May 24 14:15-14:30

Seafloor vertical displacements related to the 2011 Tohoku-Oki earthquake observed by ocean bottom pressure gauges

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Seafloor vertical displacements related to the 2011 Tohoku-Oki earthquake were directly observed by in-situ ocean bottom pressure (OBP) measurements using autonomous gauges. In the vicinity of the hypocenter of the earthquake within a distance of 100 km, eight OBP gauges recorded OBP during several months including the time of the occurrence of the earthquake. In addition, we carried out several-months OBP observations after the earthquake at five sites on a landward slope of the Japan Trench between Miyagi and Aomori. The OBP observations starting before the Tohoku-Oki earthquake revealed coseismic seafloor vertical displacements of the mainshock (Mj9.0, 5:46 UT, 11 March), the largest foreshock (Mj7.3, 2:45 UT, 9 March), and the second largest foreshock (Mj6.8, 21:24 UT, 9 March), and associated slow displacements including postseismic displacements. This presentation summarizes these observational evidences. The observed coseismic displacements were meters, tens of centimeters, and centimeters for the mainshock, the largest foreshock, and the second largest foreshock, respectively. Detecting slow seafloor vertical displacements from OBP records seems difficult because OBP signals related to the slow displacements are contaminated by ubiquitous oceanic variations. The authors developed an ocean model based on a numerical simulation, and corrected the OBP data. As a result, a slow vertical displacement of centimeters was evident at a time from the largest foreshock to the mainshock. The postseismic displacements after the mainshock were evident as a subsidence at most sites near the hypocenter region. The subsidence was large at landward sites, and reached several tens of centimeters during several months. The OBP records starting after the earthquake will be examined considering a separation of postseismic displacements and instrumental drifts.

Keywords: ocean bottom pressure, seafloor vertical displacement, coseismic slip, slow slip, postseismic slip

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SCG74-04 Room:IC Time:May 24 14:30-14:45

Evolution of the postseismic slip associated with the 2011 Tohoku Earthquake based on land and seafloor geodetic data

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On 11 March 2011, the 2011 off the Pacific coast of Tohoku earthquake (M 9.0) has occurred on the plate boundary between the subducting Pacific and continental plates. This huge earthquake has been associating postseismic deformations as well as past large earthquakes that occurred around the Japanese Islands. Especially, the postseismic slip events that were associated with recent interplate earthquakes in the northeastern Japan subduction zone, such as 1993 Sanriku-Haruka-Oki (Mw 7.6) and 2005 Miyagi-Oki (Mw 7.2) earthquakes, released moments as large as the seismic moments that were released by their main-shocks (e.g., Heki et al., 1997; Miura et al., 2006). Ozawa et al. (2011) have already reported the postseismic slip associated with the 2011 off the Pacific coast of Tohoku earthquake based on the terrestrial continuous GPS observation performed by means of a nationwide GPS array, "GEONET." The postseismic slip has been still continuing at present, but the released moment is still relatively small (< Mw 8.6 according to GSI, 2012, http://www.gsi.go.jp/cais/topic110314-index.html) comparing with the seismic moment of the mainshock, M 9.0. Therefore, we expect that the postseismic slip will continue for a while. However, we can not estimate postseismic slip at the very shallow portion on the plate interface precisely based only on the terrestrial GPS data, because such offshore areas are too far from the coast of the northeastern Japan.

Thus, We investigated the spatial and temporal evolution of the postseismic slip on the plate interface based not only on the terrestrial GPS data but also on the seafloor geodetic data such as crustal movements measured by means of GPS/Acoustic ranging and vertical displacements observed by using Ocean Bottom Pressure gauges. We estimated displacements due to large after-shocks based on their CMT solutions, and subtracted them from the original displacement time series data. A time-dependent inversion method devised by Yagi and Kikuchi (2003) is applied to estimate the postseismic slip distributions. Usages of the seafloor geodetic data significantly improve the spatial resolution of the slip distribution near the Japan Trench as well as the coseismic slip distribution.

Preliminary result shows following features; 1) Large postseismic slip has been occurring at the very shallow (< 20 km in depth) portion on the plate interface off Ibaraki, Fukushima and Iwate prefectures where huge (~50 m) coseismic slip did not occurred, 2) Significantly large slip is distributed at the deep (> 50 km in depth) plate interface beneath Miyagi prefecture where no seismic event occurs, and 3) No postseismic slip may occur at the asperities in Miyagi-Oki region that ruptured during the Miyagi-Oki earthquake in 1978 and the M 9.0 mainshock in 2011.

We will present the latest result in the meeting.

Keywords: 2011 off the Pacific Coast of Tohoku Earthquake, Crustal Deformation, Ocean Bottom Pressure, GPS/Acoustic ranging, GPS, Postseismic Slip

Japan Geoscience Union Meeting 2012
(May 20-25 2012 at Makuhari, Chiba, Japan)

SCG74-05 Room:IC Time:May 24 14:45-15:00

Temporal evolution of afterslip following the 2011 Tohoku-oki earthquake

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We use GPS data recorded by the continuous GPS network, GEONET, to investigate afterslip following the March 11, 2011, Tohoku-oki earthquake (Mw 9.0). We analyzed GPS data after March 11 with the GIPSY-OASIS II software to estimate daily station coordinates. The daily GPS time series show large-scale postseismic deformation. The observed postseismic deformation is assumed to result from aseismic afterslip on the subducting Pacific plate interface and temporal evolution of afterslip distribution is estimated using a time-dependent inversion method. In the inversion, the curved plate interface is approximated with collection of many triangular dislocation elements. The Network Inversion Filter [Segall and Matthews, 1997] is applied to the GPS time series from March 11 to October 17, 2011, to estimate temporal variation of afterslip distribution. Our inversion analysis shows that afterslip is concentrated downdip of the coseismic rupture off Sanriku, off Miyagi, and off Fukushima. We find another afterslip patch that is adjacent to the rupture area of the largest aftershock off Choshi. Our analysis does not show significant temporal variation of spatial pattern of afterslip, indicating that afterslip propagated within a few days after the mainshock. As of October 17, 2011, the maximum cumulative afterslip is 2.79 m and the moment magnitude from the estimated afterslip distribution is Mw=8.52. Residuals between the observed and predicted displacements show a systematic pattern that is consistent with postseismic viscous relaxation.

Japan Geoscience Union Meeting 2012
(May 20-25 2012 at Makuhari, Chiba, Japan)

SCG74-06 Room:IC Time:May 24 15:00-15:15

Co- and post-seismic slips of the 2011 Tohoku-oki Earthquake sequence from EOF analysis of GPS kinematic time series

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GPS kinematic time series are analyzed to estimate slip distributions for the M 9.0 2011 off the Pacific coast of Tohoku Earthquake sequence. Empirical orthogonal function (EOF) analysis is employed to enhance the signal-to-noise ratio of the original time series. The coseismic and subsequent postseismic deformations of the foreshock can be described by a single mode, suggesting that the extent of the source for both events must be similar. The total moment magnitude of the afterslip following the foreshock is estimated to be M 7.1 with a decay time of 0.63 days. The magnitude of the afterslip was larger for the duration than was anticipated by the scaling law for a typical slow earthquake, although two previous earthquakes in the adjacent regions showed the same tendency as that in the present case. No acceleration of quasistatic slip that may hint at the occurrence of a future mainshock was detected. The pattern of slips of the mainshock and the subsequent afterslips and aftershocks indicates that each slip occurs in a region adjacent to that of the previous slips in a complementary manner. Finally, in the course of the EOF analysis, the modes representing the thermal expansion of the GPS pillars are clearly identified.

Keywords: Kinematic GPS, Empirical Orthogonal Function, Coseismic slip, Afterslip

Japan Geoscience Union Meeting 2012
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SCG74-07 Room:IC Time:May 24 15:30-15:45

The 2011 Tohoku-oki Earthquake: Total Recovery of the Slip Deficit Accumulated in a Basement Asperity

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The Mw9.0 off northeast Japan (Tohoku-oki) earthquake occurred on March 11th of 2011 at the interface between the North American (NA) and Pacific (PA) plates. The occurrence of interplate earthquakes can be regarded as the sudden release of tectonic stress accumulated by the interseismic gradual increase of slip deficit in source regions. To obtain precise slip-deficit rate distribution on the NA-PA plate interface, Hashimoto et al. (2009) have analyzed GPS velocity data for the interseismic calm period of 1996-2000 with a unified inversion formula for Bayesian models with direct and indirect prior information (Matsu'ura et al. 2007). In this analysis, however, the updip limit of the model region is set to 4 km on the basis of geohydro-chemical studies for the strength of subduction zone plate boundaries, and so the inversion result might be biased especially in the shallow part of the plate interface. In the present study, to obtain unbiased slip-deficit rate distribution, we reanalyzed the same interseismic GPS velocity data with the same inversion procedure but without setting any updip limit of the model region. The result of the inversion analysis clearly shows the existence of five remarkable slip-deficit zones distributed on the NA-PA plate interface along the southern Kuril-Japan trench. We also analyzed coseismic GPS displacement data for the Tohoku-oki earthquake with the same inversion method, and obtained the bimodal distribution of coseismic slip spreading over the southern two, Miyagi-oki and Fukushima-oki, interseismic slip-deficit zones. The maximum slip is 32 m for the Miyagi-oki slip-deficit zone but only 7 m for the Fukushima-oki slip-deficit zone. The extraordinarily large coseismic slip in the Miyagi-oki slip-deficit zone, where ordinarily large earthquakes with about 3 m coseismic slips have repeated every 40 years in the past two centuries, suggests the total rupture of a 300-km-long basement asperity underlying much smaller-scale local asperities.

Keywords: the 2011 Tohoku-oki earthquake, GPS data inversion, interseismic slip deficit, coseismic slip, basement asperity

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(May 20-25 2012 at Makuhari, Chiba, Japan)

SCG74-08 Room:IC Time:May 24 15:45-16:00

Accelerated subduction of the Pacific Plate

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In NE Japan, GPS stations move landward, and the velocity gets faster as the inter-plate coupling becomes stronger (interseismic crustal deformation). Once an interplate earthquake occurs, coseismic trench-ward movements occur and subsequent slow movements continue while the afterslip lasts. We divide the plate boundary in NE Japan into three segments, i.e. (1) Tokachi-oki, (2) Aomori-oki and Rikuchu-oki, and (3) Miyagi-oki and Fukushima-oki, from north to south. There relatively stable and uniform interseismic deformation continued in 1996-2003. Since 2003 autumn, however, these three segments have been in different situations. Here we study time evolution of plate coupling in these segments from a macroscopic viewpoint.

The figure shows the trench-ward (N110E) movements of the three GPS stations in Taiki (Hokkaido), Kuji (Iwate) and Soma (Fukushima), which reflect coupling in the segments (1), (2), and (3), respectively, from the F3 solution of GEONET. Long-term trends inferred from pre-2003 data are removed to isolate changes in trend after 2003. Large coseismic movements of the 2003 Tokachi-oki (Mw8.0) and the 2011 Tohoku-oki (Mw9.0) earthquakes are removed for visual simplicity.

In Taiki, afterslip of the 2003 earthquake is obvious, and the time series after that suggests that the coupling in (1) has not completely recovered till now (positive slope still remains). Similar decoupling is seen also in the segment (3). There, the coupling seems to be progressive weakening since 2003 (positive slope gradually increases). Microscopic inspection reveals that this comes from a series of M7 class earthquakes, i.e. the 2003, 2005, 2011 Miyagi-oki events (M6.8, 7.2 and 7.3), the 2008 Ibaraki-oki event (M6.9), and the 2008, 2010 Fukushima-oki (M6.7, 6.2) events, and their disproportionally large afterslips. From macroscopic point of view, however, these earthquakes could also be interpreted as ruptures of relatively small asperities occurred as parts of a huge slow earthquake that started in 2003 and continued until the 2011 Tohoku-oki earthquake.

In the segment (2), no large interplate events occurred during this period. The Kuji GPS station, in northern Iwate, showed a sudden increase of coupling (almost double) in 2003 September as seen by a clear break in slope. It is unlikely that interplate friction suddenly increased by nearby earthquakes. Here we hypothesize that this rather reflects the accelerated subduction and consequent apparent strengthening of the coupling in the segment (2).

When a large interplate earthquake decoupled the plate interface, subducting slab would be temporarily accelerated. This, however, will not enhance the slip deficit of the adjacent segment, i.e. decoupling in the segment (1) would not accelerate the landward movement of Kuji. If the entire slab spanning from (1) to (3) behaved like a coherent body, the segment (2) would follow the acceleration of the other segments.

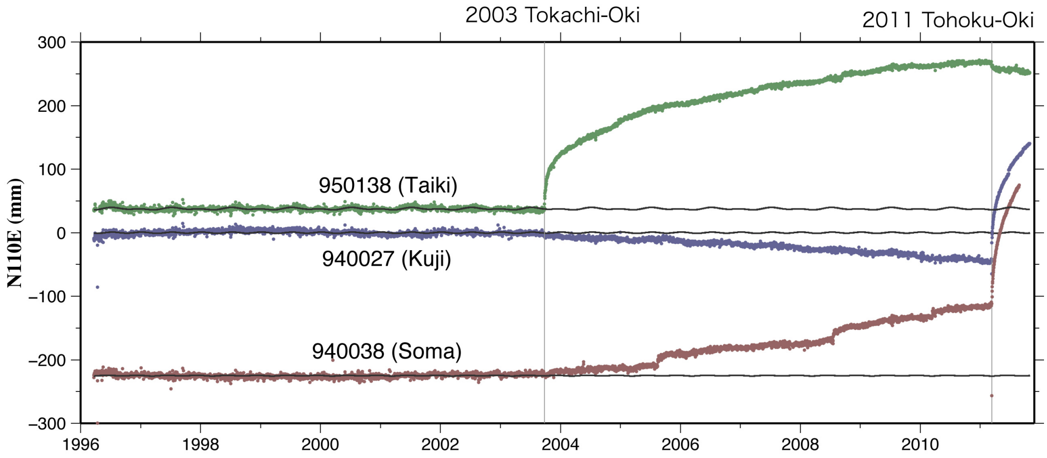
The two opposite forces are exerted on the slab near a trench, i.e. slab-pull in the down-dip direction, and friction caused by interplate coupling in the up-dip direction (the latter is visible as the slip deficit with GPS). Their balance maintains stationary subduction. Once a certain segment is decoupled, the slab pull temporarily exceeds the friction and would let the slab accelerate until the increased coupling realizes a new equilibrium. The time series of the Kuji station suggests that such an adjustment occurs in a relatively short time, say a few days.

(Figure)

Trench-ward (N110E) movement of the three GPS stations in Taiki (Hokkaido), Kuji (Iwate) and Soma (Fukushima), detrended using data before 2003. Large coseismic movements are removed for visual clarity. In response to the decrease of the coupling (trend becomes upward) at Taiki and Soma, coupling increases (trend becomes downward) in Kuji.

Keywords: Northeast Japan, GPS, Interseismic crustal deformation, Pacific plate, acceleration, 2003 Tokachi-Oki earthquake

SCG74-08 Room:IC Time:May 24 15:45-16:00



Japan Geoscience Union Meeting 2012
(May 20-25 2012 at Makuhari, Chiba, Japan)

SCG74-09 Room:IC Time:May 24 16:00-16:15

Post-seismic vertical crustal movements due to the Tohoku-Oki earthquake of 11 March 2011

KATO, Teruyuki[1*], FUKUDA, Jun'ichi[1], TANAKA, Yoshiyuki[1], AOKI, Yosuke[1]

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This presentation reports the progress of investigations on the vertical crustal movements due to the 11 March 2011 Tohoku-oki earthquake (Mw9.0), northeastern Japan. Nationwide GPS array showed more than 1m of co-seismic land subsidence along the pacific coast of the Tohoku district. While the coast was not uplifted by the co-seismic slip, it was expected that the coastal subsidence before the earthquake together with co-seismic subsidence could be recovered by the post-seismic uplift due to combined effects of a slow slip at the deeper extension of the plate interface and subsequent visco-elastic stress adjustment in the crust and the upper mantle. For example, post-seismic crustal deformations in the southern Shikoku after the 1946 Nankai earthquake had been interpreted by this mechanism.

Time series of coordinates of GEONET array after the 2011 earthquake during the first several months after the earthquake showed slight uplift of the Sanriku coast and they were assumed to be due to the slip along the deeper plate interface along the Sanriku coast (Fukuda et al., AGU Fall meeting 2011). The maximum slip amounted to about 2.5m. However, the slip is not reaching deep enough to uplift the coast efficiently. The uplift of the coast in the first half year after the main shock has been only a few centimeters. A simple extension of the transient displacements with a logarithmic function suggests that the coast will never recover the co-seismic subsidence in the coming decades of years.

Visco-elastic adjustment using a model that assumes elastic crust and a visco-elastic upper mantle, predicts a little more complicated progress of vertical motions in the area (Tanaka et al., AGU Fall meeting 2011). Though it suggests some recovery uplift, in particular, in the southern part of the source area, the whole coast will subside in the coming 1000years or longer. Such visco-elastic process may continue for more than several thousand of years and might converge to slight subsidence compared with that before the earthquake. Considering that the super large earthquake may repeat in 1000 years or so, integrated effects of visco-elastic stress adjustments may accumulates subsidence in longer time elapse, which seem to contradict with a geomorphological evidence.

One question we may have to raise, given this consequence, is that the pre-seismic subsidence along the Sanriku coast would be due not to the coupling of the plate interface but to the visco-elastic effects by one or multiple super large earthquakes that have ever occurred in the past hundreds or thousands of years. More detailed investigations will be needed to confirm the mechanism.

Keywords: GPS, Tohoku-oki earthquake, post-seismic crustal movement, crustal movement, visco-elastic adjustment

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SCG74-10 Room:IC Time:May 24 16:15-16:30

The inter-, co- and post-seismic crustal deformation in the Tohoku region by the kinematic earthquake cycle model

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The Northeast Japan arc is a typical arc formed by the subduction of the Pacific plate beneath the North American plate. The interplate earthquake has been considered to be of M7 at the maximum. However, after Mw 9.0, the 2011 off the Pacific coast of Tohoku earthquake, tectonics of the Tohoku region of the northeast Japan should be reexamined under the environment of great earthquake cycles.

From geological observations, the Northeast Japan arc is considered to be under east-west compression. The late Quaternary vertical deformation is estimated to be uplift in the whole Tohoku region, revealed from the distribution of marine and river terraces. On the contrary, geodetic observation of the recent 100 years shows subsidence up to 5˜10 mm/yr particularly on the Pacific coast. In terms of long-term balance, great uplift is expected at the great earthquake. In fact, GPS observation shows further subsidence at the 2011 off the Pacific coast of Tohoku earthquake. Therefore, it is necessary to reveal the stage of the earthquake cycle where the deformation turns to uplift, and its mechanism. On the other hand, seismicity of inland area of Tohoku is mostly reverse fault of east-west compression before the great earthquake. However, this type of earthquakes is notably decreased.

As is stated, the crustal deformation and the pattern of inland earthquake reflecting the regional stress fields are variable at each stage of the earthquake cycle. Because each of them is caused by the plate subduction and associated earthquake cycles, we should construct the model to explain these features in the big picture. One of the models is the plate subduction model with the elastic dislocation theory. In this study, we examine the temporal variation of subsidence in the later stage of the earthquake cycle, subsidence at the time of the earthquake, and long-term uplift.

In this study, we take the two-dimensional geometry of the plate interface from the vertical section of the CAMP model near the epicenter of the Tohoku earthquake. The slip on the plate interface is decomposed into 3 components: steady slip on the whole plate interface (steady subduciton), increase of slip deficit in the locked region (interseismic locking) and periodic seismic slip. We give plate relative velocity (10 mm/yr) as steady slip and assume that fracture occur each 1000 years on the locked region of the horizontal 500-km width extending to 40-km depth. In the long-term deformation model, it is necessary to consider viscoelasticity in the asthenosphere. Here, we assume elastic surface layer over viscoelastic half-space as lithosphere-asthenosphere system.

First, long-term deformation is affected only by the effect of steady subduciton, regardless of the coseismic slip. The deformation shows subsidence at the trench and uplift in the arc region, which agrees with the long-term uplift in Tohoku. The coseismic deformation shows uplift at the upper edge of the slip region and subsidence at the lower edge and inland area.

The interseismic deformation clearly depends on the extent of fracture in the elastic lithosphere. In the case of the earthquake dividing the lithosphere entirely (lithospheric thickness H = 40 km), the arc region uplifts due to the effect of the interseimic locking. In the case of the introduction of steady slip region below the coseismic slip (H = 50 km), the inland region uplifts in the 200 years after the earthquake. On the other hand, 400 years before the earthquake, inland region turns to subsidence. This result is consistent with the subsidence in Tohoku in the later stage of the earthquake cycle.

In the earlier stage, the effect of viscoelastic response to the coseismic slip is dominant and in the later stage, the intersesmic locking. The results also show the importance of the observation of the long-term deformation in the ocean area of the Pacific coast, because the vertical deformation pattern strongly depends on the distance from the trench axis.

Keywords: 2011 off the Pacific coast of Tohoku earthquake, Crustal deformation, Earthquake cycle, Viscoelasticity, Steady subduction, Tectonics

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(May 20-25 2012 at Makuhari, Chiba, Japan)

SCG74-P01 Room:Convention Hall Time:May 24 17:15-18:30

Perturbation of small repeating earthquake depending on frictional properties

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Owing to recent development of seismological observation network, small repeating earthquake analysis has been confirmed as an effective approach to estimate slip history or coupling ratio on subduction plate boundaries, especially near source regions of megathrust earthquakes where inland GPS network would have difficulty estimating it with high precision. Some of repeating earthquake analyses shows that estimated slip amount tends to be smaller than that estimated from GPS analysis. This discrepancy is thought to be caused by failure in detecting non-similar earthquakes with low cross-correlation coefficient due to stress perturbation around the source regions. Ariyoshi et al. [2007 GRL] pointed out that slow slip events temporarily occur in the deeper source region of a repeating earthquake during the passage of large postseismic slip. However, this is only one example of non-similar earthquakes, and other types of them may occur with different conditions of effective normal stress or constitutive friction law. In order to investigate it, we perform numerical simulations of non-similar earthquake with stress perturbation.

In case of slowness-law, our simulation shows that slow slip events usually occur but regular earthquakes temporarily occur under the same frictional properties and lower effective normal stress due to shallower focal depth or higher pore pressure, which is the opposite result from Ariyoshi et al. [2007 GRL]. In case of moderate effective normal stress, repeating earthquakes usually occur and become temporarily active in the passage of large postseismic slip. In case of slip-law, similar characteristics are shown but its range of effective normal stress between regular and slow earthquake is significantly narrower than that of slowness-law. The temporary activation with moderate effective normal stress could not have been reproduced by many trial simulations we have done so far. For deeper focal depth, no slip events occur for a long period before and after a large interplate earthquake. We think that such differences come from the narrow range of effective normal stress generating slow earthquake for slip-law [Ampuero and Rubin, 2008 JGR], which would be applied to stress perturbation due to large postseismic slip.

Comparing with observational results, we think that actual condition of subduction zone of the Pacific plate may obey slowness-law or slip-law under moderate effective normal stress being nearly constant over a wide depth range. Considering the fact that repeating earthquakes occur three times just after the 2011 Tohoku-oki Earthquake, we conclude that slip-law can not be applicable to the actual plate interface. In this presentation, we will discuss the validity of several types of friction laws including composite-law [Kato and Tullis, 2001 GRL] or PRZ law [Perrin et al. 1995 JMPS] as well as slowness-law and slip-law, toward developing evaluation of crustal deformation accompanied by megathrust earthquakes such as the 2011 Tohoku-oki Earthquake by analyzing repeating earthquakes and numerical simulations based on the friction law.

Keywords: non-similar earthquake, slip estimation by repeating earthquake analyses, numerical simulation based on friction law, postseismic slip propagation, effect of geofluid and focal depth, interplate earthquake, interplate earthquake

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(May 20-25 2012 at Makuhari, Chiba, Japan)

SCG74-P02 Room:Convention Hall Time:May 24 17:15-18:30

Current status and future plan of seafloor geodetic observation for 2011 Tohoku-oki earthquake

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We have detected considerably large coseismic displacement associated with the 2011 Tohoku-Oki earthquake thorough GPS/acoustic geodetic surveys. Taken them together with those observed by Japan Coast Guard and wide-spread array of seafloor pressure gauges, the data definitely contribute to elucidate the coseismic slip distribution of the earthquake based on numerical inversion analysis, the result of which we did not expected with our knowledge before the earthquake, but is supported by many other observations after the earthquake. The unexpected feature is not only in the coseismic slip distribution but also in postseismic deformation. GSI has been monitoring the postseismic deformation using GEONET and reported reasonable slip distribution that compensates the coseismic slip of the main shock mainly in the western (and hence deeper) adjacent area. However, our repeated observations after the earthquake indicate complexity in the postseismic slip, including further slip even at the main coseismic slip area near the trench. In addition, the deformation seems to still continue with a considerable rate.

To elucidate the complexity, Tohoku University and Nagoya University plan to drastically extend the seafloor geodetic survey sites along the Japan Trench by this summer under the accelerated project promoted and funded by MEXT. The total number of survey sites being planned is about 20, to be distributed mainly on deeper seafloor near the trench, in where the deformation cannot be inferred from onshore GPS network. The most of the survey sites consist of four transponders while some important sites consist of six transponders, which can effectively correct the effect of undesired spatial variation in sound speed in ocean. The new transponders are designed against long ranging over 10 km distant at depth and are compatible with both the systems of the university groups and Japan Coast Guard.

The other key of the project is the introduction of an autonomous moving buoy, which can navigate itself along programmed path or remotely operated on demand away from a research vessel. The utilization of this extra buoy will lead surveys to be more efficient or precise taken with an existing towing buoy simultaneously. The power for electronics and propulsion will be supplied by diesel oil lasting for at least two days per fuel. The autonomous buoy is an all-in-one system and the allover length is 3 m at most, which can be dealt with any researcher on any vessel. This promotes new research groups to begin their own GPS/acoustic survey. Systematic result of displacements in postseismic deformation will be obtained after the second time of survey to be conducted by the end of the fiscal year of 2012.

Keywords: 2011 Tohoku-Oki earthquake, seafloor crustal deformation, postseismic deformation, seafloor geodesy

SCG74-P03 Room:Convention Hall Time:May 24 17:15-18:30

Postseismic deformation following the 2011 off the Pacific coast of Tohoku earthquake and its mechanism

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The postseismic deformation caused by the 2011 off Pacific coast of Tohoku earthquake exceeds 90 cm for 10 months after the main shock. The coseismic subsidence area begins to uplift except for the area in the Iwate prefecture. Estimated afterslip exceeds 3.0 m and extends to west, south and north of the coseismic slip area with a moment of 9.15 x 10^{21}Nm for 10 months. The area of the afterslip was extended westward and reaches a depth of approximately 90 km of the subducting plate. Northern and southern edges of the area of afterslip seems to be limited by the source region of the 1994 Sanriku-Haruka-oki earthquake and the north limit of the overriding Philippine Sea plates, respectively.

We report the latest status of the postseismic deformation and estimated afterslip model in the meeting. We also report the deformation due to the other mechanisms, such as viscoelastic and poroelastic rebound.

Keywords: 2011 off the Pacfic coast of Tohoku earthquake, postseismic deformation, afterslip, viscoelastic relaxation, poroelastic rebound

SCG74-P04 Room:Convention Hall Time:May 24 17:15-18:30

Spatio-temporal distribution of afterslip due to the 2011 Tohoku-Oki earthquake from MCMC inversion

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INTRODUCTION

The 2011 off the Pacific coast of Tohoku Earthquake (Mw9.0) occurred at 5:46 a.m. on March 11, 2011 (UTC). In north-east Japan, an earthquake of magnitude 9 has first recorded in history. Moreover, the information of the huge earthquake is poor in the world. On the other hand, national GPS observation network (GEONET) observes detail of crustal deformation. GEONET observes eastward post-seismic displacements due to the Tohoku-Oki earthquake on the plate interface. We asuume that the post-seismic displacement is due to an afterslip. In order to understand earthquake, it is important to infer stress state and frictional behavior on the plate boundary from spatio-temporal distribution of afterslip (Hsu *et al.* ,2006). Hence, we estimate spatio-temporal distribution of afterslip due to the 2011 Tohoku-Oki earthquake.

GPS DATA

In this study, we used daily coordinates of GPS station (F3 solution), which is observed by GEONET and analyzed by Geospatial Information Authority of Japan (GSI). The period of observation is from 1996 to now. In this period, the time series of crustal deformation include a liner trend, annual variations, and co- and post-seismic deformations. They can be modeled by a linear, trigonometric, Heaviside-step and logarithmic functions, respectively. We estimate these model parameters using least square method for linear part and the interior-reflective newton method for non-linear part (Coleman *et al.* , 1996). We extract the post-seismic displacements due to the Tohoku-Oki earthquake through a modeling of time series of crustal deformation.

INVERSION METHOD

We use a method based on a Markov chain Monte Carlo (MCMC) Method to estimate the spatiotemporal distribution of after-slip. The conventional inversion method, such as least squares method, estimates one solution for each unknown parameter. On the other hand, MCMC method estimates probability density functions (PDFs) of each unknown parameter. Especially, MCMC method represents an under-determined problem as the correlation between each solution. To estimate afterslip distribution, the observation equation, representing a relation between observed data and the afterslip distribution, is written as $\mathbf{d} = \mathbf{G}\,\mathbf{m}$. Here, $\mathbf{d}$ is an observation data, $\mathbf{m}$ is afterslip of every sub-fault in strike and dip directions, and $\mathbf{G}$ is a Green function that is the coefficient matrix which defines a relation between $\mathbf{d}$ and $\mathbf{m}$, and including the coefficient of Laplacian smoothing parameter. In this study, we use a Green function considered a 3-dimensional heterogeneous structure in northeast Japan, which is produced by 3D Finite Elements Method. In the smoothing parameter, we employ weighted Laplacian smoothing regularized by scale of the Green function. The sampling method of MCMC is Metropolis-Hastings algorithm. In order to enhance computational speed, we use GPU (Graphics Processing Unit), because MCMC method needs large amounts of calculations.

RESULTS

Mainly afterslip locates in depth range between 25 and 35 km, and in width range of 400km, which is below the co-seismic slip distribution (Simons *et al.* , 2011). The peak of afterslip is about 3m in Fukushima-Oki after 7 months from the Tohoku-Oki earthquake. This area agrees with the area of the 1983 Fukushima-Prefecture-Oki earthquake. For the temporal change of after-slip, the large afterslip started at off the Fukushima prefecture. After then, afterslip move to off the Iwate prefecture. Furthermore, the spatial distribution of residual is similar pattern of interseismic strain concentration area.

Keywords: Tohoku-Oki earthquake, afterslip, Malcov chain Monte Carlo method, Green function using FEM

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(May 20-25 2012 at Makuhari, Chiba, Japan)

SCG74-P05 Room:Convention Hall Time:May 24 17:15-18:30

Temporal changes of Toki ACROSS signal induced by the 2011 off the Pacific coast of Tohoku Earthquake

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[1]Takahiro Kunitomo

Temporal changes of waveform and travel time of Toki ACROSS signal observed by Hi-net induced by the 2011 off the Pacific coast of Tohoku Earthquake (2011 Tohoku Earthquake as follow) are repoed. At Toki station, the current specifications of seismic signal being transmitted since Mar. 2007 (ongoing for ˜ five years) are as follows: FM signal with a carrier frequency of 13.005 Hz, modulation period 50s in the frequency range 10.245-19.445Hz and ˜2700N in spectrum amplitude. The signal and operational mode of rotary transmitter with the vertical rotation axis are optimized for acquiring the accurate tensor transfer function data in frequency domain and Green's function in time domain between the source and receivers located anywhere.

The major results observed at Hi-net Yaotsu (11.3km form Toki station) are as follows:

1) Difference waveforms between daily stacked waveforms and a reference waveform stacked one year data (Apr. 2008 to Mar. 2009) show notable changes of P and S wave later phases after March 11, 2011. These changes are decaying as the month move on, but waveforms do not return to its former state as at December 2011. These changes are thought to be due to groundwater fluctuation induce by the 2011 Tohoku Earthquake.

2) Daily travel time changes of maximum amplitude phases (including direct P wave, direct S wave and these later phases) were calculated using the cross-spectral method. Travel time changes up to 2 msec delay was detected at March 11, 2011. This changes are decaying as the month move on, but travel times do not return to its former state as at December 2011.

Acknowledgement: Hi-net data are provided by National Research Institute for Earth Science and Disaster Prevention, Japan (NIED). Toki ACROSS transmitting station is managed by Japan Atomic Energy Agency (JAEA).

Keywords: travel time change, crustal movement

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Detection of tsunami-induced deformation caused by the 2011 Tohoku earthquake using on-land GPS network

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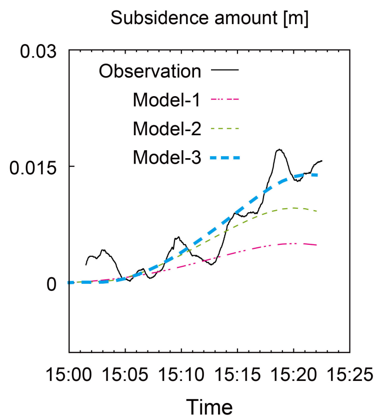
The 2011 Tohoku earthquake on March 11 caused massive tsunami. We first detect a land-deformation signal due to the tsunami using on-land GPS network. We focus on GPS stations along the Sanriku coast, and stack the GPS data at seven coastal stations and seven landward stations respectively. The data show that relative subsidence at the coastal stations to the landward stations had occurred on the order of 1 cm until almost 30 minutes after the Tohoku earthquake. We check whether the subsidence signal corresponds to simulated land deformation based on a tsunami simulation model, and confirm the tsunami hypothesis for the subsidence. We find that a popular elastic model with a stratified velocity structure (Gutenberg-Bullen earth model) for the Green's function leads to underestimation of the subsidence amount about 1/2-1/3. Effect of compliant materials near the surface may be important to estimate tsunami-induced land deformation.

Keywords: The 2011 Tohoku earthquake, tsunami, load deformation, comparison between observation and simulation



SCG74-P07 Room:Convention Hall Time:May 24 17:15-18:30

Gravity changes due to the 2011 Tohoku earthquake recorded by superconducting gravimeters

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The 2011 Tohoku earthquake caused large scale crustal deformations, both coseismic and postseismic, in a wide area of the Japanese islands. As a result, surface gravity must have indicated not only coseismic changes but also long-term changes. In addition, secular changes due to the viscoelastic properties of the crust and the mantle may be observed in gravity recordings.

This earthquake is the first event in which three superconducting gravimeters (Mizusawa, Matsushiro and Kamioka) were in operation not far from the source region of an M9 class earthquake. Although these gravimeters suffered from severe disturbances due to the main shock and the aftershocks, they have been producing almost continuous recordings of gravity. As the data are accumulated, crustal deformations as seen from gravity may be revealed by long term gravity observations with the superconducting gravimeters. We are working on separation of the signals by making corrections for the atmospheric and hydrological effects on gravity.

Keywords: superconducting gravimeter, 2011 Tohoku earthquake

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Mechanism of induced earthquakes of the 2011 Off Pacific coast of Tohoku Earthquake according to aftershocks activity

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Many induced earthquakes occurred after the Off the Pacific coast of Tohoku Earthquake in 2011. According to the GPS-network measurement, the Northeast Japan expanded more than 5m to the east. This means that a tensional stress affected to the upper crust and the stress field of the upper crust of Northeast Japan would be reduced. So, the fuluids occured in the lower part of the upper crust, and uplifted into the upper part of the upper crust. This is causing the induced earthquakes.

Keywords: induced earthquake, mechanism, hipocentral distribution, geologic structure, reduced stress, uplifting by fluid

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Geomorphologic analysis of the co-seismic deformation of the seabed in the tsunami source area of the Tohoku Earthquake

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Abstract

The 2011 off the Pacific coast of Tohoku Earthquake happened on March 11, 2011, generated huge tsunamis and caused many fatalities and missing in the Hokkaido, Tohoku and Kanto regions.

According to Japan Agency for Marine-earth Science and Technology, JAMSTEC, seabed topography in off the coast of Tohoku deformed at the giant earthquake event by active faults along the Japan Trench.

We identify a series of faults from bathymetric data obtained before and after the giant event. Bathymetric data after the earthquake had acquired by KH11-7 cruise of the JAMSTEC R/V Hakuho-maru and YK11-E06 cruise of the JAMSTEC R/V Yokosuka in 2011, and the data before earthquake were acquired and compiled by Japan Coast Guard.

By deciphering and comparing the coseismic deformation of the seabed in both map view and vertical sections, we confirmed the location and attitude of the active faults that caused great slip at the shallow tip of the plate boundary.

The resultant slip model corresponds to the relationship of seabed topography with tsunamigenic displacement in the tsunami source region.

The rises located in the center of the trench bottom are asymmetric in profile, the landward side dips gentle and the seaward side is steeper. They are chained almost north-southerly, in the trench floor from 38o02' to 38o05'N, about 5.5 km.

Examined the correspondence between the results of geomorphlogical analysis and the slip distribution models, the distribution of asymmetric ridges formed by the earthquake is ristricted in the area 143o57'~144o03E', and 38o00'~38o07'N and almost coincide with large displacement area in slip distribution model in Iinuma et al.(2011).

The trench floor west of the anticlinal ridges and the lower landward trenchslope display apparent uplift by about 50 m, while no significant change was detected in the seaward.

From this we can consider that, the asymmetric ridge is caused by reverse faulting of the plate interface, and the layers of trench floor sediment were deformed in a style of detachment fold.

The fault scarps distributed on the landward trench-slope before the earthquake were disappeared after the earthquake. This is because the hanging wall of a spray fault might be raised to caused the giant tsunami.

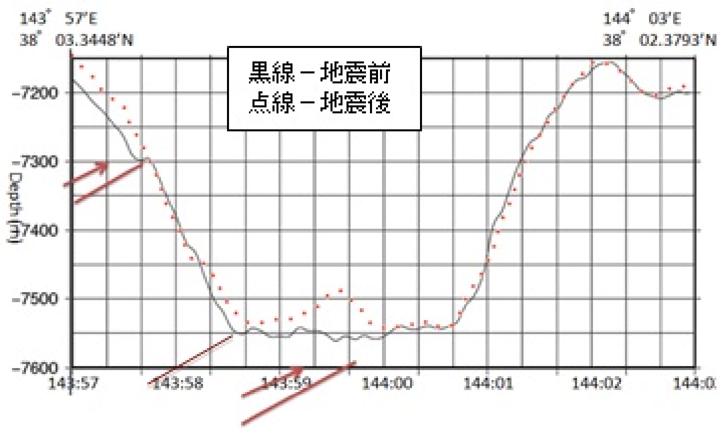
In the landward trench-slope many new landslides and fault scarps were formed. Numbers of small landslides appeared along the fault scarps. Some of them are accompanied by sedimentary terraces.

Consequently, we estimated the trench floor and the landward trench-slope were uplifted and displaced seaward by the coseismic slippages of the decollement surface and splay faults during the giant earthquake. Such seafloor deformation conformed by this study might explain the reason of the sharp peak wavelet of the giant tsunami.

Those changes in seafloor topography due to large slip of the decollement surface and the splay faults during the earthquake, we may provide one of criteria in screening of slip distribution models.

Keywords: Off Tohoku Earthquake, Geomorphological Change, Morphological survey, The KH11-07 Cruise, Japan Trench, Seafloor Faults

SCG74-P09 Room:Convention Hall Time:May 24 17:15-18:30



Japan Geoscience Union Meeting 2012
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SCG74-P10 Room:Convention Hall Time:May 24 17:15-18:30

The Great Eastern Japan Earthquake 2011 and Its Mechanisms According to the Theory of Solid State Lithologic Flow

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1. Introduction

The Great Eastern Japan Earthquake, hit Tohoku and Kanto districts in Japan on March 11th 2011, was estimated 9.0 in its magnitude. It is the greatest earthquake which Japanese have ever experienced. However, it brought us very curious evidences to reconsider the orthodox theory about mechanisms of great earthquakes. Especially, the key for understanding seems to be the theory of solid state lithologic flow. Therefore, we discuss it in this paper.

2. A question about mechanisms of great earthquakes

The orthodox theory about mechanisms of great earthquakes was based upon plate tectonics and thermal mantle convection. However, the theory of solid state lithologic flow also explains that. Althogh it appears as if the two theories were able to explain the same phenomena, **the primal difference between them lies on the force which causes the crustal movements**.

3. Orthodox theory

The orthodox theory explains the great earthquakes with plate tectonics. The theory premises on thermal convections within mantle. This theory also premises that **the internal thermal energy in the Earth creates the force to drive convections**. To the east of Japan there is Japan Trench. The Pacific Plate lies under the bottom of the Paciphic Ocean east of Japan Trench. The orthodox theory supposes that there is a current of thermal mantle convection that flows under Japan Trench from the Paciphic Ocean side, and that the mantle convection drag the Paciphic Plate into the layer under Japan. Therefore, the Japan Islands are gradually subsiding with the Paciphic Plate. However, because the specific gravity of the continental Plate including the Japan Islands is smaller than the Paciphic Plate, the buoyancy makes a sudden rise after a while. At that sudden rise, a great earthquake and a great tsunami occur. **Nevertheless, coast subsidences were observed instead of coast upheavals.** This fact is enough for us to doubt the orthodox theory.

4. Mechanisms of the earthquake based on the theory of solid state lithologic flow

Please look at the figure.

A) As if it were a glacial flow, the solid state lithologic flow from higher places to lower places is made by gravity.

B) Since the Japan Trench is a very low place, the solid state lithologic flow flows into the trench. Therefore, there is the forefront of the flow on the trench.

C) The forefront of the flow run into the lithologic plate of the bottom of the Pacific Ocean. Then, it run over the plate.

D) It is the heavy weight of the forefront of the flow running over the Pacific plate, that push the Pacific plate into the Earth.

E) The lithologic plate of the bottom of the Pacific Ocean is gradually pushued deep into the Earth.

The causal chain of working force is following: **A->B->C->D->E**.

There is nothing but gravity to work. Thermal mantle convections have no place in this theory.

Since the movement C is a very sudden phenomenon, the great earthquake and tsunami occur.

The phenomena occur in the reverse order: **E->D->C->B->A**, because it is a repeated current.

5. The comprehension with the theory of solid state lithologic flow

It is possible for us to take one set understanding of these two phenomena: (1) the 5.3m movement toward the east and (2) the 1.2m subsidence of the sea coast (Both are observed at Ojika Peninsura).

These phenomena gave us evidences to understand the movement of the Japan Islands as a solid state lithologic flow. It flows from higher places to lower places. It flowed 5.3m to the east horizontally while it flowed down 1.2m vertically (Denoted by A).

It is possible for us to understand these movement as a movement of the whole Japan Islands with a current of solid state lithologic flow.

This explanation based on the new theory, which takes the lithologic flows as same as glacial flows, gives us very clear understanding without any difficulty.

Probably the sharply pointed shape of Ojika Peninsura has been created by repeated diastrophism like this time.

Keywords: Diastrophism, Earthquake, The Great Eastern Japan Earthquake 2011, Tsunami, Solid State Lithologic Flow, Gravity

SCG74-P10 Room:Convention Hall Time:May 24 17:15-18:30