Japan Geoscience Union Meeting 2012
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An interpretation of the Tohoku Earthquake in terms of a damage zone/asperity model of faults

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1. Introduction: We proposed a damage zone/asperity model of faults to interpret the source parameters of an earthquake in terms of the physical properties of a fault zone (Yamamoto & Yabe, 2003, 2006 in SSJ meeting). Here, we will apply this model to the Tohoku earthquake to estimate the fault zone thickness and the recurrence time of the earthquake.

2. Model of Faults: In this model, a fault zone consists of the damage zone and the asperity zone. The damage zone is defined to be the zone filled with rocks under the post-failure state. The zone is incompressible and non-rigid for quasi-static shear deformation, but elastic for dynamic deformation. In the asperity zone, intact rocks support shearing force applied to the fault zone boundaries between the fault zone and intact rocks outside of the fault zone. Thus, the shear stress imposed on the fault zone boundaries is supported only by the asperity, while the normal stress is supported by whole the fault zone.

The rupture breaking from the asperity propagates into the damage zone to form a slip-plane. No shear stress is assumed on the slip-plane after faulting as inferred from the stress measurements. The size of a fault plane is determined by equilibrating the released energy from the asperity and the rocks outside of the fault zone with the apparent fracture energy and the seismic energy. The apparent fracture energy is almost equal in magnitude to the work done by the vertical displacement due to the rotation of a damage zone against the normal stress. The energy is proportional to the fault zone thickness. Denoting the areas of the fault plane and the asperity by S and s, respectively, f = s/S is estimated at a few percent at most.

Consider a fault zone of a uniform thickness t_d, of which the length is l. The relationship between t_d and l is expressed by

$t_d = 0.0016*l$.

The shear strength tau_f of the asperity is approximated by

$tau_f = r*e_f$,

where r and e_f respectively are the rigidity and the strength in terms of shear strain. The asperity is assumed to fracture at the time that the strain reaches to its critical value of e_f. The relative displacement u_c for e_f between the fault zone boundaries is expressed by

$u_c = t_d*e_f$

u_c is called by the critical displacement. e_f is assumed at 0.01 hereafter.

Here we assume a circular crack in a uniform host rock to evaluate the strain energy released from the rocks outside of the fault zone and the displacement between the fault zone boundaries. The crack surface is identical in size to the slip plane. The seismic energy is expressed by

$E = h*(8/7)*r*(l/2)^3*(f*e_f)^2$,

where h denotes the seismic efficiency and f is the function of h. The average displacement is given by

$u_{bav} = 8*l*f*e_f/(7*pi)$

The displacement on the slip plane is written by

$u = u_c + u_b$

When the crack is buried, the magnitude of an earthquake is approximated by

$M_s = \log(S) + 4.0$

for h around 0.7.

3. Application to the Tohoku Earthquake: The aftershock area of the Tohoku earthquake is about 500 km in length and 200 km in width (JMA, 2011). If we take this length as the fault length, the followings are determined; t_d = 0.8 km, u_c = 8 m, u_{bav} = 20 m, and the largest of u_b is about 28 m for h = 0.7. The largest of the displacement on the slip plane, that is about 1.4 times of u_{bav}, is estimated to be about 36 m. This suggests the recurrence time of M9 earthquakes more than 450 years for the average slip rate of 8 cm/y. The area of the circular crack is about $2*10^5$ km^2. M is determined at 9.0 by taking into consideration that the energy has been released from the half area of the circular crack in the underground.

4. Conclusion: The above result suggests that the magnitude of an earthquake is determined by the thickness of the fault zone where the fractured asperity has existed or the G-R rule depends on the thickness distribution. In order to estimate the magnitudes of the potential earthquakes on the fault, it is important to clarify the distribution of fault zone thickness.

Keywords: fault model, damage zone, weak faults, critical distance, The Tohoku earthquake, recurrnce time

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Dynamic triggering of earthquakes in Kyushu during the passage of seismic waves from the 2011 Tohoku earthquake

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During the passage of waves from the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0) (hereafter, the 2011 Tohoku earthquake), early post-earthquakes were observed over the Japanese Islands (Miyazawa, 2011). In Kyushu, local events were also observed at that time. Such events have already been detected and located (Enescu et al., 2011; Hirose et al., 2011; Miyazawa, 2011; Obara and Matsuzawa, 2011). In this study, we detected triggered earthquakes more carefully. We then located hypocenter and tried to determine the focal mechanism solutions by using the P-wave polarities.

We detected events from seismograms recorded at 142 stations of Kagoshima University, Kyushu University, the Japan Meteorological Agency, and Hi-net in Kyushu. The time window is between 14:52 and 14:59 (JST) when the body and surface waves from the 2011 Tohoku earthquake run though Kyushu. The dominant periods of the body and surface waves from the 2011 Tohoku earthquake are much longer than those of the waves of local events because of higher attenuation of shorter-periods components for long-distance propagation (~1600 km). We tested several filters preliminarily, and we chose a band-pass filter of 16-32 Hz, which help us to pick arrival times of body waves easily. We used the HYPOMH program (Hirata and Matsu'ura, 1987) for hypocenter location with a 1D velocity structure model which is used for the routine hypocenter determination in Kagoshima University. We determined the focal mechanisms by using a program developed by Kobayashi and Nakanishi (1994).

We detected more than 30 earthquakes, and estimated 14 hypocenters and 4 focal mechanisms. These events distribute volcanic and high seismicity areas. This result is consistent with Miyazawa (2011). The focal depths
are shallow. The focal mechanisms differ from those of the background seismicity. We infer that the dynamic stress changes due to the seismic waves may differ from the background stress field.

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Strain of the East Japan Super Earthquake M9.0 have been accumulated around marginal swell of Pacific Plate

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The third aftershock M7.5 just 40 minits after East Japan Super Earthquake occurred at outside of the Japan Trench. The aftershock of outer trench earthquake with forcal mechanism of normal fault was a fracture caused by pulling force on the Pacific Plate just after the removal of obstacle to subduct, and can be treated as the simplest example in the plate dynamics. The outer trench earthquake occurs simply with reaching over the limit of fracture by the balance of pushing and pulling forces along the trench. The normal fault type focal mechanism is caused by excess of pulling force of subducting slab over pushing force.

The analysis are carried on the hypocenter of initial shock and CMT (Centroid Moment Tensor) focal mechanism of 128 outer trench earthquakes in the last 17 years are available from Homepage of Meterorological Agency. Because the normal fault type forcal mechanisms were counted 95, which overwhelm the reverse fault type of 26, we can suggest the driving force of the motion of the Pacific Plate is slab pull along the trenchs.

Japan Trench had been on a condition of exess pushing force with reverse fault type outer trench earthquakes since December 2008 after the last normal fault type outer trench earthquake of Nobember 2005, however, exess pulling force conditions had been along Kuril Trench since January 2009, Ogasawara Trench since August 2008 and Izu Trench since Septmber 2010. The East Japan Super Earthquake can be understand as an event of the removal of obstacle to subduct by the pulling forces along the Kuril Trench and Izu-Ogasawara Trench, both wings of Japan Trench.

The consisitensy between the distribution of 54 normal fault type outer trench earthquakes after the Super Earthquake and the slip distribution drived from the inversion analysis on strong motion at the Super Earthquake, indicates that the strain of the Super Earthquake have been accumulated not on East Japan side, but on outer trench side of Pacific Plate and the duration for accumulation of the strain is shorter than 6 years since November 2005.

The strain release has not been observed after the Super Earthquake along the East Japan, as occurring of reverse fault type earthquakes, subsidence of more than several tens cm along the Pacific coast on the trend of subsidence with the rate 1cm/ year for the last 100 years. Tsunamite for Keicho-Sanriku Earthquake 16011 requires wide source area over Japan Trench and Kuril Trench. Tsunami of the East Japan Super Earthquke also requires source area along Japan Trench.

The maximum slip at the Super Earthquake of 50m requires width of zone for accumulation of the strain of 500 km ~ 5000km, coreponding rate of ten thousandth and hundred thousandth for strain limit of fracture on the crust. The required zone is too wide for the narrow inhomogenous East Japan side, but capable for the Pacific Plate side with the distance of 5000km to Hawaii. Pacific Plate has Marginal Swell along the trench chain with positive gravity anormally. The gravity anormally represent that the uplifting Swell is supported by the forces against isostasic balance. The pushing up force for the swell should be directely related with flexure for the subduction of Pacific Plate along the trenches. The Swell gives flexibility to maintain constant rate of plate motion against accidental obstacle to subduct along trenches, which means that the strain for the earthquake along the trench can be accumulated in the flexure of Marginal Swell. Tsunami might be induced by reducing flexure on the swell just after the earthquake.

The results supports that the strain for the East Japan Super Earthquake had been acculated in the flexure of Marginal Swell. The wide tsunami source area represented by the Tsunamite for Hoei-Nankai Earthquake 1707 and Yaeyama Earthquke 1771 can be also explained by the Marginal Swell along Nankai Trough and Ryukyu Trench.

Keywords: Marginal Swell, outer trench earthquake, plate dynamics, gravity anomaly, slab pull, East Japan Super Earthquake

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Sea surface gravity changes observed prior to March 11, 2011 Tohoku earthquake

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The 2011 Tohoku earthquake occurred at the subduction of oceanic tectonic plate, where we had no historical record of this size of huge earthquake. We have examined ship board geophysical observations conducted above the source rupture area if there are any indications of large slip before the earthquake. We have examined ship board geophysical observations conducted above the source rupture area if there are any indications of large slip before this earthquake. We have found that there were two cruises, which pass almost the same tracks above the source rupture area near the oceanic trench, where many researches indicate that there were coseismic large slip, and compared sea surface gravimeter measurements along these tracks. Sea surface gravity measurement conducted one month before the earthquake shows that there was an increase of sea surface gravity with about 10 mGal (1Gal=1cm/s2) compared to the sea surface gravity value measured three months before the earthquake. The measured gravity changes can be interpreted as a density increase along the fault surface of which time scale of evolution is about three months. This observation provides physical mechanism to explain how this large and slow slip can be generated along this fault

Keywords: The 2011 Tohoku, Japan Earthquake, Sea surface gravity mesurements, Earthquake rupture process

SSS39-P05 Room:Convention Hall Time:May 25 13:45-15:15

Video image of seafloor near the epicenter of the 2011 Great Tohoku Earthquake

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Video image of seafloor near the hypocenter of the 2011 Tohoku Great Earthquake will be presented. The image was obtained during an operation for retrieval of ocean bottom monitoring instruments using an ROV, remote operating vehicle. At the occurrence of the Tohoku Earthquake, on Mar. 11 2011, almost 20 instruments were in place. Although we tried to retrieve these instruments by ordinary acoustic releasing, some of them did not come up and it seemed that they were arrested at the seafloor. We sent an ROV to recover four ocean bottom pressure recorders (OBPRs) deployed near the epicenter of the mainshock. Although no remarkable deformation associated with strong seafloor motions could be observed, it was found that fine-grained sediments covered the seabed. The sediments were not consolidated at all and the thickness was about 15 cm. The sediments covered the bottom parts of the OBPRs. Judging from the pressure records, it appears unlikely that the OBPR sank into the sediments due to hard shaking during the strong ground motion. It seems that flung up particles fell and piled up on the seabed after the earthquake.

Keywords: video image of seafloor, ocean bottom instruments

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High resolution seismic imaging in the trench axis area of the Japan trench off Miyagi

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Since the great Tohoku earthquake occurred, we have conducted multichannel seismic surveys using tuned air gun array with large volume (7800 inch^3) and long (˜6 km) streamer cable to image the ruptured area in the landward slope of the Japan trench. Obtained seismic sections successfully delineated the structural characteristic. We also carried out a high resolution seismic survey using a cluster gun with smaller volume (320 inch^3) and shorter (˜1.3 km) streamer cable in the vicinity of the trench axis area. The survey was a part of the site survey for IODP Japan Trench Fast Earthquake Drilling Project, thus a 2-D grid lines with 500 m line spacing were planned to determine the best location of the drilling site. Due to the higher frequency contents of the source and denser spacing of hydrophones, we could obtain finer scale of the structural image. In the trench axis area, pelagic/hemiplegic sediments were folded and cut by reverse faults. A seaward dipping reflector, gently connecting the edge of the horst and the top of the graben, is imaged in the migrated section. We could obtain high resolution seismic images in the Japan trench area, despite the great depth of the seafloor, small volume of the source and short maximum offset of the streamer cable. However, any continuous reflectors are not imaged inside of the the frontal prism, seaward of the ”backstop” interface. This observation suggests that significant lithological boundary or well developed fault does not exist in the frontal prism of the Japan Trench.

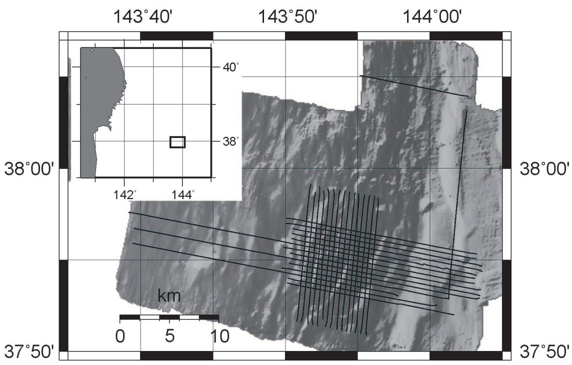

Fig. Survey lines of the high resolution MCS carried out during the KY11-E05 cruise.

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P-wave velocity structure in the southernmost source region of the 2011 Tohoku earthquakes, off the Boso Peninsula

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The Japan Trench (JT) is a plate convergent zone where the Pacific Plate (PAC) is subducting below the Japanese island. In the southern end part of the JT, there is a trench-trench-trench type triple junction. The Philippine Sea plate (PHS) is subducting northwestward from Sagami Trough and the PAC is subducting westward beneath the PHS from Japan and Izu-Bonin Trenches. The deep seismic structural information is important to understand the evolution of the triple junction. In 2008, a seismic experiment was conducted using ocean bottom seismometers and controlled sources comprising ariguns and explosions in the off-Ibaraki and Boso Peninsula. This region is the southern edge of the rupture zone of the 2011 off the Pacific coast of Tohoku Earthquake. We estimated the heterogeneous velocity structure beneath the landward slope of the southernmost JT by 2-D ray tracing. The crustal structure in the southern part of the profile is more heterogeneous than that of the northern part beneath the seismic survey profile. The subducting PHS is imaged beneath the southern part of profile. However, we could not obtain the distinct image of contact zone of PHS and PAC. It is conceivable that the contact zone of PHS and PAC has large heterogeneity resulting from strong deformation. We infer that the termination of the rupture of the 2011 Tohoku Earthquake and the large afterslip in the collision region are caused by this strong heterogeneity.

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Structural discontinuities inside the Pacific plate offshore the Tohoku region, revealed by seismic reflection imaging

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We have investigated the material properties and the tectonic processes that govern the Pacific plate just before it is subducted in the Japan Trench Subduction zone. We reprocessed the 500 km long data retrieved by the summer 1991 seismic survey offshore of the Boso peninsula and Tohoku regions and produced a high resolution image of the Pacific plate crust and Mantle lithosphere beneath it. We have conducted a CMP gather analysis combining 18828 traces and applied a first arrival mute at almost every 4 shots. Consecutively we applied NMO corrections after determining stacking velocity values every 30 CMP gathers, which is equivalent to every 800 m along the profile. The corrected traces enabled us to retrieve a high resolution image of the sediments deposited on the Pacific plate. The upper part of the plate is characterized by a thick sequence of sediments offshore of the Boso peninsula that becomes progressively thinner towards the north in the region offshore the Tohoku region. This could be due to the geometry of the profile, since the southern part is further away from the trench than the north. Offshore Tohoku the sediments are possibly eroded and redeposit inside the trench by down going currents. Our profile intersects with a seamount range that is currently subducting under the Japan Trench. The sedimentary sequence on the Pacific plate around this range is disturbed by a thick sequence of possibly volcanic origin sediments derived from the seamount range. The sedimentary units offshore Boso peninsula display an uplift of several hundred meters. This could suggest that the area of the Pacific plate behind the triple junction point with the Japanese Arc and Philippine Sea plate is under a compressive regime.

Keywords: Tohoku, Reflection, Pacific plate

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Precise aftershock distribution of the 2011 off the Pacific coast of Tohoku earthquake revealed by ocean bottom seismogr

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The 2011 off the Pacific coast of Tohoku earthquake occurred at the plate boundary between the Pacific plate and the landward plate on March 11, 2011, and has a magnitude of 9. Many aftershocks occurred following the mainshock. To obtain a precise aftershock distribution is important for understanding of mechanism of the earthquake generation. In order to study the aftershock activity of this event, we carried out extensive sea floor aftershock observation using more than 100 ocean bottom seismometers just after the mainshock. Deployment and recovery of the OBS were repeated four times, and we use the data from more than 70 OBSs just after the mainshock to the middle of June, 2011. We selected 1908 events whose epicenter is located below the OBS network form the JMA earthquake catalog, and P and S-wave arrival times were picked from the OBS data. Hypocenters were estimated by a maximum-likelihood estimation technique and one dimensional velocity structures was modeled using the results of previous refraction study in the study region. Thickness of sedimentary layers changes at each OBS site was evaluated and the estimated travel times by the location program was corrected. A precise aftershock distribution for approximately three months in the whole source area, with an emphasis on depths of events, using the OBS data was obtained. The OBS networks located 1005 earthquakes with a high spatial resolution. The epicenter distribution is not uniform. In the epicenter distribution, the aftershocks may be divided into a number of clusters from a geometrical view point. The aftershocks form a plane dipping landward in the whole area. Comparing our results to velocity structures by marine seismic surveys, there is no aftershock along the plate boundary in the region off Miyagi, where a large slip during the mainshock is estimated. A plate coupling in this region may change due to occurrence of the mainshock. Activity of aftershocks within the landward plate above the source region is high and many aftershocks within the landward plate have normal fault type or strike-slip type mechanism. On the other hand, many events with reverse fault (thrust) type mechanism occur along the plate boundary. Within the subducting oceanic plate, most of earthquakes has normal fault type or strike-slip type mechanism. The stress field in and around the sources region of the 2011 mainshock changes as a results of the mainshock.

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Near-trench aftershock activity of the 2011 Tohoku-oki earthquake

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After the 2011 Mw 9.0 Tohoku-Oki Earthquakes, normal-fault type aftershock activity have been observed both in the overriding plate and incoming/subducting Pacific plate near the trench axis [e.g., Asano et al., 2011]. Several tens of meters slip along the plate boundary occurred near the trench axis during the 2011 Tohoku-Oki earthquake [e.g., Fujiwara et al., 2011]. This large co-seismic displacement reached to the trench axis. The normal-faulting aftershocks near the trench axis are likely caused by a tensional stress due to such large slips along the plate boundary. Detail distribution of the aftershocks near the trench axis and their focal mechanisms are important information for considering the large co-seismic displacement along the plate boundary reaching to the trench axis and crustal structures near the trench axis.

We conducted ocean bottom seismograph (OBS) observations using 10 OBSs near the Japan Trench from August to October 2011. These OBSs were deployed on the landward slope including the area, where the several tens of meters co-seismic displacement was observed, with approximately 10 km separation in horizontal. In addition to these OBSs, we used OBSs deployed for aftershock observations continued from soon after the 2011 Tohoku-Oki earthquake [Shinohara et al., 2011]. Preliminary results of the hypocenter locations show that several earthquakes occurred within the overriding plate. These earthquakes may relate to the normal fault system in the overriding plate. On the other hand, other earthquakes are located mainly in the subducting oceanic crust. We will discuss relationships among aftershock activity near the trench axis, crustal structures obtained from the active seismic surveys, and large co-seismic displacement reaching to the trench axis.

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Precise aftershock relocation of the 2011 Tohoku earthquake and its relation to regional slip distribution

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One of the characteristics of the 2011 Mw 9.0 off the Pacific coast of Tohoku earthquake is a quite large co-seismic slip at a shallow part of the Japan Trench plate interface. Knowing precise aftershock distribution is a key to clarify the mechanism of the earthquake with such a new aspect. Especially, understanding relationships between the slip distribution and the aftershock activity provides an important clue for elucidating the source rupture process.

Therefore, in this study, we precisely relocated the aftershocks by using data from 20 ocean bottom seismometers (OBSs) deployed between 37N and 38N where the amount of co-seismic slip showed a remarkable transition. The observation area is about 150km x 150km and the station interval is about 25km. We relocated the events in the Japan Meteorological Agency Catalog data from March 28, 2011 to July 12, 2011.

We manually picked arrival times of the PS wave converted at the bottom of the sedimentary layers as well as P and S waves of each aftershock, and located its hypocenter by using hypomh (Hirata and Matsu'ura, 1987). We applied station corrections determined from a time difference between P- and PS-wave arrivals at each station. We utilized the results as the initial hypocenters, and obtained their final hypocenters by applying hypoDD (Waldhauser and Ellsworth, 2000). We used a 1-D velocity structure derived from an existing velocity section (Miura et al., 2003).

Comparing our result to subduction velocity structure (Miura et al., 2005) lying to the north of the study area, it is shown that the aftershock activity along the plate interface between the continental plate and the subducting Pacific plate is low at shallower than 20km depth. In contrast, many aftershocks occur both along the plate interface deeper than 20km depth and within the continental plate. Low aftershock seismicity appears concordant with a large co-seismic slip estimated by previous studies. In addition, the swarm like activity around the oceanic Mohorovicic discontinuity is confirmed at the up-dip of a large co-seismic slip area near the Japan Trench axis.

Keywords: the 2011 Tohoku earthquake, aftershock, slip distribution, subduction, ocean bottom seismometer

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Deep structure of subducted slab beneath the seismogenic zone of the 2011 off the Pacific coast of Tohoku Earthquake

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The coseismic rupture area of the 2011 off the Pacific coast of Tohoku Earthquake has estimated over the wide region from the coastline to near the Japan Trench [e.g., Ide et al., 2011]. Several kinds of studies, such as tsunami source inversion [e.g., Fujii et al., 2011], submarine topography [Fujiwara et al., 2011] and seafloor displacement observation [Sato et al., 2011; Ito et al., 2011; Kido et al., 2011], showed consistent results. However, the structural image just beneath the largest coseismic slip area was unclear since the observation areas of previous ocean bottom seismographs (OBSs) in this region were limited and there were few OBSs near the Japan Trench. The resolved area of Yamamoto et al. [2011] was limited to within about 100 km from the coastal line, and the main shock of the 2011 earthquake located out of resolved area. To understand the relationship between coseismic rupture behavior and structural heterogeneities, it is necessary to know the seismic velocity structure of the subducted slab crust and mantle near the trench axis.

Japan Agency for Marine-Earth Science and Technology has conducted the aftershock observation at outer rise from May 2011 to June 2011. From this observation, more than 1,000 earthquakes were detected [Obana et al., 2012]. These aftershocks included the relatively large ($M > 3$) earthquakes, and their travel time data were also obtained at land seismic stations. In addition, Tohoku University deployed some OBSs in the landward slope of Japan Trench at the same time [Suzuki et al., 2012]. Combining these OBS dataset and land seismic data, we could obtain the travel time data between the coastal area and outer rise area with high accuracy of hypocenter locations.

In this study, we perform a three-dimensional seismic tomography from Miyagi Prefecture to outer-rise region by tomoFDD [Zhang and Thurber, 2006]. For the preliminary analysis, we estimate the P-wave velocity structure by using a part of dataset. For initial velocity model, we adopted the three-dimensional model of Yamamoto et al. [2011] for landward slope area and one-dimensional model of Obana et al. [2012] for outer rise area. Our results indicate that the velocity of uppermost slab mantle from 143 degrees E to the trench axis is relatively slower than that in outer rise and coastal area. This result seems to be independence from initial velocity model from some test calculations. On the other hand, our present dataset has few OBSs on the landward slope near the trench axis. We will add the dataset of joint observation conducted by Universities (Hokkaido, Tohoku, Chiba, Tokyo, Kyushu, and Kagoshima), JAMSTEC, and Meteorological Research Institute to obtain more detail structural image.

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Seismic activities of earthquake clusters and small repeating earthquakes in Japan after the 2011 Tohoku earthquake

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The 2011 off the Pacific coast of Tohoku earthquake (Mw9.0) was the largest earthquake in recorded history in Japan. The coseismic slip expanded into the areas covered the occurrence areas of interplate earthquakes off Iwate to off Ibaraki, northeastern Japan. For the impact of this earthquake, the seismic activities in and around the source regions have changed significantly. In this study, I investigated spatio-temporal changes of seismic activities of earthquake clusters and small repeating earthquakes in Japan after the mainshock. Furthermore, I estimate the space-time characteristics of the interplate slip from sequences of small repeating earthquakes.

I have already reported slip-rates in the 21st century before the 2011 mainshock at the upper boundaries of the subducting plates. The resultant slip-rates correspond to relative plate motion in the Ryukyu arc. In contrast, they indicated slip deficits in the northeastern Japan arc. There were few postseismic slips following the 2005 off Miyagi prefecture earthquake (M7.2), which located near the hypocenter of the 2011 mainshock. On the other hand, slip deficits were slightly decreased in the southern shallow part of the northeastern Japan after postseismic slips following the 2003 off Miyagi earthquake (M6.8), the 2008 off Ibaraki earthquake (M7.0), and the 2008 off Fukushima earthquake (M6.9). Furthermore, I identified quasi-static slips associated with foreshocks off Miyagi that started from 2011.

After the 2011 mainshock, I detect many small repeating earthquakes. They distributed in the northern, southern and deeper part of the source region. Small repeating earthquakes with relatively long recurrence intervals occurred just after the 2011 mainshock. The cumulative slips are consistent to the value estimated by GPS data analysis in the northwestern deeper part. My result also suggests postseismic slips at the trench-side of the southeastern part. On the other hand, I can not detect small repeating earthquakes in some areas of source region. Distributions of small repeating earthquakes may suggest zero or slightly slipped areas in the 2011 mainshock and the largest aftershock. Some of small repeating earthquakes are burst-type sequences which occurred only after the 2011 mainshock. Observed seismograms may be distorted by the multiplicity of the waves to come from various locations, the seismic velocity changes at the propagation path or site, or changes of physical properties at the plate interface. I also detected many small repeating earthquakes beneath the Kanto district. They suggest induced interplate slips at the subducting Philippine Sea plate and the subducting Pacific plates. In other areas, I can not identify noticeable velocity increases.

Furthermore, I automatically extracted earthquake clusters by using the unified JMA hypocenter catalogue and investigated seismicity changes before and after the mainshock at each earthquake cluster. As a result, I identified that seismic activities after the mainshock have become active in the deeper part of the source region. The largest earthquakes in the analysis period have occurred in some clusters including small repeating earthquakes after the 2011 mainshock. In addition, they activate in several areas around the Kanto, Tokai, and Ryukyu areas of the Philippine Sea plate, and the inland shallow part of eastern Japan. On the other hand, seismic activities decrease with some clusters in the source areas and many intra-plate clusters in intermediate-depths. It suggests the large effects of interplate large slips and stress changes at the mainshock and/or postseismic slip. We should pay attention to future activities to investigate whether physical property at these areas has changed or not.

Keywords: The 2011 off the Pacific coast of Tohoku earthquake, earthquake cluster, small repeating earthquake

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Seismic activity in the focal area of the 2011 Tohoku earthquake in comparison with off-Kamaishi repeating earthquakes

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To investigate the seismic property of the fault zone for the 2011 great earthquake is of great importance for understanding the mechanism of M9 earthquakes. The studies on the off-Kamaishi repeating earthquake sequence (e.g., Uchida et al., 2012) suggest following features of the asperity for the recurrent earthquakes. 1) The asperity has a hierarchical structure. 2) The seismicity in the interseismic period is active near the edge of the asperity and less active around its center. 3) The temporal change in seismicity shows low seismicity just after the main shock to high seismicity in the latter half of the earthquake cycle. 4) Migration of smaller earthquakes (earthquakes near the center of the focal area of the main shock follows those near the edge of the area) are sometimes observed. These features probably show the difference in interplate coupling and unfastening of the asperity during the earthquake cycle. In this study, we investigate the seismic activity in the focal area of the 2011 Tohoku earthquake and compare it with that of the off-Kamaishi repeating earthquake sequence.

Several interplate earthquakes with M7 or larger after 1930 are located in the slip area for the 2011 Tohoku earthquake. Thus the 2011 earthquake also shows a hierarchical structure (feature 1). Most of the the M>=7 earthquakes are located near the edge or outside of the main slip area for the 2011 earthquake (Yamanaka and Kikuchi, 2004; Murotani et al., 2006; Yamanaka, 2011). The Miyagi-oki area has M7 repeaters at the deeper edge of the slip area, which is similar to the repeating earthquakes near the deeper edge of the off-Kamaishi sequence. Inactive seismicity near the center of slip area is also true of the 2011 earthquake and major activities near the center were observed in 1981 (M7.0) and 2011 (M7.3) (feature 2). The repeating earthquakes and low-angle thrust type earthquakes (Asano et al., 2011) are inactive in the main slip area for the 2011 earthquake and this may be a part of temporal seismicity change in the earthquake cycle of the M9 earthquakes (feature 3). Migration of earthquakes from around the edge toward the center of the focal area of the 2011 earthquake has been sometimes observed (e.g., seismic activities off Fukushima in 1938 and off Sanriku in 1968). These activities similar to the off-Kamaishi earthquake sequence (feature 4) may be manifestations of invasion of slip toward the center of the asperity.

For the 2011 Tohoku earthquake, we successfully estimated spatial-temporal change in the interplate coupling in and around the slip area using small repeating earthquakes, which was difficult for the source area of the off-Kamaishi earthquake. Unfastening of the coupling in the source area of the Tohoku earthquake was observed in 2008 off Fukushima and Miyagi prefectures (Uchida et al., 2009; Graduate School of Science, Tohoku University, 2010). Many repeating earthquakes are included in the aftershocks of the 2011 M7.3 foreshock, which probably also shows the unfastening of the coupling. High-coupling coefficient in a wide area and lack of repeating earthquakes near the trench can also characterize the asperity for the great interplate earthquake.

The characteristics of the seismic activity in and around the source area of the 2011 Tohoku earthquake mentioned above are similar to the off-Kamaishi sequence in many aspects. These features might be true of simple systems only; but if they are common for most of seismogenic patches, it is quite important not only for understanding the earthquake generation process but also for the disaster mitigation through the detection of hidden asperities for great earthquakes.

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Twin-peaks slip distribution of the 2011 Tohoku Earthquake and its relation to the foreshock and aftershock activities

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Previously, Hiratsuka and Sato (2011) investigated the Coulomb stress change for the hypothetical receiver faults to evaluate the effect of the 2011 Tohoku Earthquake on aftershocks and future earthquake probabilities. They assumed the slip distribution determined immediately after the event using the GEONET data by the Geospatial Information Authority of Japan (GSI). The slip distribution gives the area of maximum slip lying almost halfway between the coast line and trench. Based on the calculated Coulomb stress changes, Hiratsuka and Sato (2011) suggested that the normal-fault aftershocks near the Japan Trench should occur within the subducted Pacific plate whereas the normal-fault aftershocks on the west of approximately 20 km depth contour of the plate interface should occur in the crust above the plate interface. Later, Sato and Hiratsuka (2011) evaluated the Coulomb stress change for the 81 larger aftershocks of which fault plane solutions are provided by Nettles et al. (2011). There they used the slip distributions determined using the GEONET data by themselves. As different slip distributions were obtained from inversion of the GEONET data depending on the strength of constraints put on the initial slip distribution, they compared the Coulomb stress change calculated for two extreme cases, that is, a slip distribution with the area of maximum slip shifted toward the land and a slip distribution with the area of maximum slip shifted toward the trench. The comparison indicated that the aftershock focal mechanism distribution is better explained by the slip distribution with the area of maximum slip shifted toward the trench. During the course of these previous studies, it was suggested that the slip distribution of the 2011 might be better constrained by considering the aftershock focal mechanism distribution as well.

In this paper, we investigate the level of consistency between the slip distribution of the 2011 Tohoku Earthquake and the aftershock distribution more closely. Since more accurate slip distribution is desirable for that purpose, we determine the slip distribution by using the coseismic displacements observed at the ocean bottom sites as well as the GEONET data. The fault geometry is assumed to be the same as that of Sato and Hiratsuka (2011). The slip distribution thus obtained is characterized by the two peaks of slip separated by a relatively low-slip zone extending in east-west direction off the border of Miyagi and Iwate Prefectures. This feature is robust and well constrained by the combination of the GEONET and ocean-bottom observations. Looking closely at the aftershock distribution near the trench, we find the place where the aftershock distribution protrudes from the trench toward the land (not towards the sea). This place coincides with the low-slip zone sandwiched by the two peaks of slip. Moreover, major seismic activities prior to the 2011 Tohoku earthquake since 1978 Off-Miyagi earthquake are distributed along the low-slip zones sandwiched by the two peaks of slip. Based on the analyses of stress field due to the slip distribution with the two peaks of slip, we investigate the cause of the interesting correlation described above.

Keywords: Subduction zone, Great earthquake, Coulomb stress change, Aftershock activity, Foreshock activity

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Envelope broadening of S-waves from earthquakes near the hypocenter of the Tohoku-Oki earthquake.

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We investgated envelope broadening and delays of peak arrivals of S waves that radiate from the aftershocks of the 2011 Tohoku-Oki earthquake on an onshore seismic network. The onshore seismograms of earthquakes occurring in the forearc of the northeastern Japan show clear difference in their S-wave envelope shapes according to difference in those focal depths (Gamage et al, 2009; Koga 2010). The seismograms of interplate earthquakes tend to have broader S-wave envelopes than those of intraplate earthquakes. Focal mechanism of earthquakes in the focal area of the 2011 Tohoku-Oki earthquake indicate that thrust faulting earthquakes, dominant earthquakes before the occurrence of the M9 mainshock, have been almost extinct around the hypocenter (Asano et al., 2011). This remarkable difference of focal mechanisms suggests that focal depth distribution of those events is largely different before and after the Tohoku-Oki earthquake. Consequently, it will be expected that characteristics of S wave seismograms of the those earthquakes in the focal area of the M9 earthquake should have also changed.

We analyzed 1Hz seismograms recorded at the seismic stations in the forearc side of the NE Japan. Root means square (rms) envelopes of velocity seismograms of horizontal components are calculated in four frequency bands 2-4, 4-8, 8-16, and 16-32Hz. As a result, most of the S-waves of the earthquakes occurring before the M9 mainshock show delays of peak arrivals and envelope broadning, originating from the characteristics of interplate earthquakes. Among the records of the aftershocks of the M9 mainshock, the envelopes of S-waves show clear onset and narrower envelopes, indicating that those earthquakes could occur within the Pacific plate. We also identify several seismograms with broad S-wave envelopes. Since no thrust type earthquakes were identified in the region, these earthquakes could occur in the hanging wall side plate of the NE Japan.

Keywords: the Tohoku-Oki earthquake, interplate earthquake, intraplate earthquake, S coda wave

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Multiple time-window tsunami waveform inversion of the 2011 off the Pacific coast of Tohoku, Japan earthquake

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We performed a multiple time-window analysis of tsunami waveform inversion for the 11 March 2011 off Pacific coast of Tohoku earthquake (M 9.0), and estimated the slip distribution. The 2011 tsunami was recorded instrumentally on coastal tide or wave gauges and offshore gauges such as ocean bottom pressure (OBP) and GPS wave gauges. The offshore gauge records within the source area showed two-stage tsunami waveforms which have a gradual increase of water level followed by an impulsive wave. The coastal run-up and inundation heights were also measured by many researchers, and the large peak appeared around Miyako in Iwate prefecture. Our previous result of tsunami waveform inversion (Fujii et al., 2011, Earth Planets and Space) assuming a simultaneous rupture of subfaults indicated that the largest slip of about 48 m occurred near the trench axis off Miyagi. However, the computed coastal tsunami heights from this model show a peak on northern Miyagi coast and did not reproduce the distribution of the measured tsunami heights.

In this study, we adopted multiple time windows on each subfault for the tsunami waveform inversion analysis assuming a constant rupture velocity in order to estimate the slip distribution both in space and time. This inversion scheme allows us to estimate a time delay of slip on each subfault after the rupture front arrived at an edge with the assumed velocity. The number of time windows is five for each subfault. Each time window has a duration of 30 s as a rise time of slip. We added four more subfaults at the northern end of the subfault model introduced by Fujii et al. (2011), and also used tsunami waveform records at more gauges than the previous study. In total, we used 11 OBP gauges, 10 GPS wave gauges and 32 coastal tide or wave gauges. The observed tsunami waveform data were resampled at an interval of 12 s to be used for the inversion. The new result indicates that the fault slip propagated from the epicenter and took about 3 minutes to reach the northern and southern ends of the source area. The large slip along the Japan trench axis is more extended than the previous result, with the maximum slip of 36 m. The slips along northern trench are about 10 m and more. The computed coastal tsunami heights from the updated model with delayed slips show another peak on central Iwate coast, where the largest tsunami heights were measured. We also computed tsunami inundation areas in Sendai and Ishinomaki plains and found that they explain the distribution of the 869 Jogan tsunami deposits. While we previously proposed the fault models of the Jogan earthquake (Satake et al., 2008; Namegaya et al., 2010, An. Rep. Active Fault and Paleoearthq. Res.), the 869 source could have been the same as the 2011 source.

Keywords: 2011 Tohoku earthquake, Tsunami waveform inversion, Multiple time windows, Coastal tsunami height, Inundation modeling

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Tsunami waveform analysis of the foreshock (Mw7.3) of the great Tohoku-oki earthquake

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On March 9, 2011, the largest foreshock (Mw7.3) occurred before the 2011 great Tohoku-oki earthquake (Mw9.0). The epicenter of the foreshock was located about 60 km northeast from the epicenter of the 2011 great Tohoku-oki earthquake. The tsunami was generated by this foreshock and observed by two ocean bottom pressure gauges, TM1 and TM1, off Kamaishi and three GPS buoys operated by the Nationwide Ocean Wave Information Network for Port and Harbors (NOWPHAS). In this paper, we estimate the fault model which explains the observed tsunami waveforms. The tsunami is numerically computed by solving the linear long-wave equations. We assumed that the fault parameters, strike=188.1 degree, dip=12.0 degree, rake=73.3 degree. The fault length and width are varied to find the best fault model which explains the five observed tsunami waveforms. The best fault model we found has a length of 40 km and a width of 55 km and is located northwest from the epicenter. In other words, the epicenter is located almost southeast corner of the fault model. The estimated slip amount by comparing the observed tsunami waveforms with the computed ones is 1.25m. The calculated seismic moment is 1.27 x 10^{20} Nm (Mw 7.3) which is similar to the seismic moment estimated by JMA using teleseismic body-waves, 1.34 x 10^{20} Nm. One day aftershocks of this foreshock occurred mostly north from the epicenter. Our estimated fault model is consistent with the one-day aftershock distribution. Kato et al. (2012, Science) suggested that the propagation of slow slip from the epicenter of the foreshock to the epicenter of the mainshock of the 2011 great Tohoku-oki earthquake. Our estimated fault model also indicates that the foreshock did not rupture the plate interface located south of the epicenter where the slow slip occurred after the foreshock.

Keywords: foreshock of the 2011 Tohoku-oki earthquake, tsunami waveform analysis, fault model

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Origin of the surface vibrations of the Sea of Japan generated by the 2011 off the Pacific coast of Tohoku Earthquake

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Just after the Tohoku earthquake on March 11, 2011, sea surface vibrations were observed at some tide stations along the coast of the Sea of Japan. In this study, we made numerical computation to generate these vibrations from a source model based on observed data of the Pacific Ocean - such as tide stations (JMA, JCG), ocean bottom tsunami sensors (ERI), offshore GPS wave gauges (NOWPHAS). As a result, we could successfully reproduce the observed vibrations of the Sea of Japan with the initial condition of not only the vertical but also of the horizontal displacement of ocean bottom.

This earthquake caused tsunami. About 30 minuates after the earthquake, tsunami attacked the Pacific coast of Tohoku with more than 9 m height according to the records of many costal tide gages.

Immediately following the earthquake, some vibrations were observed at several tide stations of the Sea of Japan. Judging from the records, the wave frequencies were rather high (the periods were about several minutes) with the amplitudes about 10 cm. Inferred from the observed data, tsunami passed the Tsugaru cannel 2 hours after this earthquake. It indicates that these vibrations were different from the tsunami that passed the Tsugaru channel.

In general, tsunamis are assumed to be long waves and the vertical deformation of ocean bottom is assumed to be instantaneous. Under these assumptions, the initial condition of numerical computation of tsunami, that is, the displacement of water surface is equal to the vertical displacement of ocean bottom. The effect of the horizontal deformation is usually neglected. This is valid as long as the ocean bottom is flat or shallowly-dipping. However, according to Tanioka and Satake (1996), if the ocean bottom contains steep slopes or steps, the effect of the horizontal displacement of ocean bottom cannot be neglected. In this study, we computed the water level of the Sea of Japan including the effect of the bathymetry and horizontal displacement of ocean bottom.

For the computation a 30s-interval grid bathymetry data (JTOPO30) was used for 128-148E longitude and 39-46 N latitude. WThe fault model, which consists of 40 rectangular subfaults, was inverted from the observed waves (Fujii et al., 2011). Then static deformation of the seafloor was calculated by using formula of Okada (1985). To calculate tsunami propagation, the linear shallow-water, or long wave, equations are numerically solved by using a finite-difference method. Finally we compared the observed and computed waveforms at every observed station.

The result indicates that only vertical displacement of ocean bottom cannot explain the vibrations of the Sea of Japan just after the earthquake, although the long-period waves were computed. Adding horizontal displacement of ocean bottom generated the vibrations similar to the observed. The horizontal displacement slightly increased the computed tsunami amplitudes at the stations along the Pacific Ocean though the waves themselves were almost the same of those from only vertical displacement.

Although the slopes of ocean bottom are located many places in the Sea of Japan, vibrations with larger amplitudes were especially observed from Akita to Sado coasts. One reason is that there exist some steep slopes or steps parallel to the fault. Another reasonis that the above regions are nearer to the fault so that ocean bottom deformation is relatively larger. There are very few changes along the Pacific Ocean because the effect of vertical displacement of ocean bottom is much more dominant than that of the horizontal one.

We computed the vibrations of the Sea of Japan just after this earthquake. However, the waveforms themselves are not so similar to the observed. This is because we ignored the effect of the non-linear terms of equations near the coast and we computed with 30s grid-interval (about 1km-interval) so that the coast topography near the tide stations is very rough.

Keywords: the 2011 off the Pacific coast of Tohoku Earthquake, tsunami, the Sea of Japan, horizontal displacement of ocean bottom

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Variability of high-frequency excitation patches estimated by strong-motion data for the 2011 Tohoku-Oki earthquake

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Using K-net and KiK-net strong-motion seismograms along the Tohoku-Kanto costal area, we characterize several notable high-frequency excitation patches for the 2011 Tohoku-Oki earthquake. We first obtained displacement seismograms with static offsets from the original acceleration waveforms recorded at K-net and KiK-net stations. For a baseline offset, we attempted several approaches, finding the correction scheme of Iwan et al. (1985) to provide us with stable and reliable displacement seismograms in all the three components.

The resulted seismograms show very large static components or steps over 5 m in some cases. For a given seismogram, there are several isolated steps in displacement, implying that there are patches to radiate these static or very low-frequency waves over the fault plane of this earthquake. The ratio of a static component to the strength of accelerations in each section of record in time (i.e., wavelet), however, varies significantly.

Considering the static component corresponding to the seismic moment (zero-frequency limit) at each patch, we measured its ratio of high-frequency and static components. We adopted the root-mean-square amplitude as a parameter for the strength of each record section, then it was divided by its static component or offset. We compared this ratio of one patch to that of the other.

The second large wavelet in each acceleration seismogram gives very low ratios, that is, static components are abnormally large, compared with the other wavelets, about one third in the radiation of high-frequency waves. Yoshida et al. (2011) located this wavelet in acceleration in the east of the epicenter, that is, a shallow part of the fault plane near the axis of the Japan Trench. Our result supports the idea that very smooth fault slips took place there, although it should not have been tsunami-earthquake type anelastic fault motions because there are still large excitations of high-frequency waves as high as 1 Hz.

We find a weak but clear delayed wavelet in acceleration only at the northernmost stations (north Iwate Prefecture) in our analysis. The ratios of high-frequency versus static component are as high as those of the first large wavelet in record, which was estimated in the location near the epicenter (Yoshida et al. 2011). That is, this northernmost patch radiates large high-frequency, suggesting strong local plate coupling in this area.

One additional wavelet that has not ever been analyzed in previous studies is a delayed one (nearly 2 minutes of the origin time) observed only in the southernmost stations in Fukushima and north Ibaraki prefectures. The ratios of high-frequency versus static components are even higher than the first patch by a factor of over 5. This implies a very strong patch that dominantly excited high-frequency waves without much total seismic moment there. This wavelet, which is composed of at least two separated parts in some records, seem to correspond to a spot off Fukushima coast identified by strong-motion array studies (e.g., Honda et al., 2011), which might be related to the asperities of a series of M7 Shioya-Oki earthquakes in 1938 (Abe, 1977).

In summary, there are various ratios of patches on the fault of the 2011 Tohoku-Oki earthquake, implying very complex nature of fault motions from place to place over the fault plane.

Keywords: 2011 Tohoku-Oki earthquake, excitation of high-frequency seismic waves, strong-motion accelerograms, static displacement

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High-frequency rupture areas during the 2011 off the Pacific coast of Tohoku Earthquake inferred from seismic intensity

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The source process of the 2011 off the Pacific coast of Tohoku Earthquake (Mw9.0) was complex and included multi sub-events. From the view of strong ground motion, there were two major peak waveforms observed around Tohoku district. These were caused by two major sub-events off Miyagi Prefecture near the epicenter. We divided each observed strong motion time history into two parts related to the two sub-events based on visual judgment. The inversion analysis was carried out to reveal high-frequency rupture areas using measured seismic intensity related to each sub-event as well as the whole event. We found that the first high-frequency rupture area was located near the hypocenter and extended northward. The second high-frequency rupture area had a substantial overlap with the first one and was nearer coastline of Miyagi Prefecture than the first, and its magnitude for seismic intensity is the same as the first. The result of the whole event shows that the high-frequency rupture areas consist two major parts. The north major part is related to two sub-events off Miyagi Prefecture. The south major part was located off-shore area near the north of Ibaraki Prefecture. Furthermore, we found that the first high-frequency rupture area was similar to that of the 1793 Kansei earthquake that was one of the major historical earthquakes in this region and the west of the high-frequency rupture area of the first two sub-events was overlapped with those of historical M7 class earthquakes off Miyagi Prefecture in 1861, 1897, 1936, 1978 and 2005 more or less. It shows that the events off Miyagi Prefecture do not be treated as simple characteristic earthquakes.

We compared the high-frequency rupture areas with the source processes presented by other researchers. At first, compared to the strong motion generation area (SMGA) models proposed by three research groups, our result is quite similar to the SMGAs of Kurahashi and Irikura (2011) in terms of rupture sequence and location. Secondly, the comparison with the rupture front process obtained from far-field P-waves using the back-projection method by Zhang et al. (2011) reveals that the three high-frequency rupture areas correspond to northward first rupture off Miyagi up to 60 seconds from origin, southwestward second rupture off Miyagi in next 40 seconds and southward third rupture from off-Fukushima to off-Ibaraki in final 40 seconds, respectively. Finally, compared to the source process obtained from joint inversion using near-field strong motion, teleseismic and geodetic data by Koketsu et al. (2011), we find that the first high-frequency rupture area corresponds to slowly expanded rupture process from the hypocenter, the second one corresponds to westward rupture with large slip from the trench accompanied with tsunami, and last one corresponds southward rupture up to off-shore of north Ibaraki Prefecture. The energy centroids of the second and last high-frequency rupture area are located at terminal rupture area of asperities. We have detected the same characteristics in the analysis of other historical interplate events [Takemura and Kanda (2008)].

Keywords: seismic intensity, inversion analysis, high frequency, the 2011 off the Pacific coast of Tohoku Earthquake, historical earthquake off Miyagi Prefecture, source process

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Rupture process of the 2011 Tohoku-Oki earthquake inverted from teleseismic body waves and geodetic data

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Rupture process of the 2011 off the Pacific coast of Tohoku earthquake is estimated from the inversion of teleseismic body waves and geodetic data. In order to obtain a reliable source model, the following are done in this study: (1)The assumed values of the maximum slip duration at each subfault (T_{sd}) and the propagation velocity of the first time window (V_{ftw}) , which have a significant influence on the source model estimated by the multiple time window analysis, are selected as objectively as possible; (2)The joint inversion of teleseismic body waves and geodetic data is done; (3) Considering the 3D shape of the plate boundary, a realistic fault model is assumed; (4)In the calculation of the teleseismic Green's functions, different 1D structure models are used for subfaults with different locations along dip direction, considering the horizontal (along dip direction) heterogeneous structure of the continental plate; (5)Not only terrestrial crustal deformation data but also seafloor crustal deformation data is used as the geodetic data; (6)A spatial and temporal smoothing constraint considering that the fault rupture reached the trench axis is used; (7)Relative weights among different kinds of data-set are determined by theoretical tests.

The estimated seismic moment and the maximum slip are $3.4 * 10^{22}$ Nm (M_w=9.0) and 43 m. The total rupture duration is about 150 s. The derived slip model has one large slip area, which is located on the shallower side of the rupture starting point and extends to the north and south along the trench axis. This model is consistent with the slip distribution estimated from the tsunami records and the results of the bathymetric survey. The estimated rupture propagation velocity is about 2 km/s when the rupture propagates from the rupture starting point towards the shallower part of the fault plane.

Keywords: the 2011 off the Pacific coast of Tohoku earthquake, rupture process, joint inversion, teleseismic body waves, geodetic data

SSS39-P23 Room:Convention Hall Time:May 25 13:45-15:15

Detailed stress fields in the focal region of the Tohoku Earthquake; Implication for the distribution of moment release

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A giant earthquake of Mw 9.0 occurred off the Pacific Coast of the Tohoku region on March 11, 2011. We examined the focal mechanism distributions in the focal region of this earthquake before and after the mainshock using the F-net data and then performed a stress tensor inversion by using the multiple inverse method(Otsubo et al., 2008). It is found that earthquakes were mainly reverse fault type events all over the focal region before the main shock, whereas after the main shock, many normal fault type events occurred in the hanging wall but focal mechanisms did not change in the deepest part in the focal region(Asano et al., 2011). It is inferred from the stress tensor inversion that the stress state is reverse fault type in the deepest part before and after the mainshock but that in the central part, the stress state changed from reverse fault type before the mainshock to normal fault type after the mainshock. These results suggest that absolute strength along the plate boundary is very weak in the central part(Hasegawa et al.,2011; Yagi and Fukahata, 2011). Furthermore, we examined the focal mechanism distribution and stress states in the shallower part near the trench axis off the Miyagi Prefecture in detail and found that the strike slip events with the P-axis in the NS direction occurred in the footwall east of the mainshock hypocenter, which can be well explained by the slip model with a large moment release near the hypocenter. It is expected that these findings well constrain the spatial distribution of moment release of the 2011 off the Pacific Coast of Tohoku earthquake and lead to better understanding of this earthquake.

Keywords: focal mechanism, stress inversion, multiple inverse method, fault model, seismic moment release, stress change

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Strength of the M9 Tohoku Earthquake generating fault

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The 2011 off the Pacific coast of Tohoku Earthquake with a magnitude (M) of 9.0 (the M9 Tohoku Earthquake) occurred at an intermediate depth (approximately 24 km) on the subducting plate interface, whereas the usual Miyagi-oki earthquake had been expected to occur at the down-dip side. A huge area of the plate interface, including asperities of the M7-class Miyagi-oki earthquakes and their surroundings, was ruptured at the mainshock, although the surroundings were previously assigned as stable sliding regions. The interplate coupling of the source region of the M9 earthquake had been believed to be weak because small repeating earthquakes were rarely occurred, but new estimates suggest high coupling coefficients in this region (Uchida & Matsuzawa, 2011, EPS). Now the questions arise: "What is the difference between the asperities of the usual Miyagi-oki earthquakes and the source region of the March 11 event, and why the M9 earthquake occurred at the region where small repeating earthquakes are almost absent".

Geophysical observations (Ito et al., 2005, GRL; Miura et al., 2005, Tectonophysics) suggest the existence of subducted seamounts at the neighborhood of the hypocenters of the M9 Tohoku Earthquake and the 1978 Miyagi-oki Earthquake. It is possible that ruptured seamounts at the depth behave as regular asperities and that uncollapsed seamounts at shallower parts act as barrier against frictional sliding.

Assuming the upper surface materials of the subducting slab to be siliceous sediments with the thickness of 2-3 km and seamounts of basaltic compositions, the strength envelope for the interplate thrust fault in NE Japan was drawn. A dislocation creep flow law of fine quartz rocks was applied for the rheology of siliceous sediments. The occurrence of repeating earthquakes at deep regular asperities is well accounted for by rheological contrast between basaltic (or gabbroic) rocks and wet quartz. The hypocenter of the M9 earthquake corresponds to the upper limit of the brittle-ductile transitional zone of wet quartz. The failure of this high-strength zone was possibly triggered by the collapse of the subducted seamount. The propagation of the coseismic slip to the down-dip part of the thrust fault is understood by the velocity-dependence of viscous/frictional properties in the brittle-ductile transitional zone.

Keywords: The 2011 off the Pacific coast of Tohoku Earthquake, asperity, rheology, subduction zone, frictional law, seamount

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Simulations of the 2011 Tohoku giant earthquake cycle including the change of plate coupling in Off-Fukushima

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The 2011 Tohoku giant earthquake ruptured the vast area extending from Off-Miyagi to Off-Ibaraki, and the Mw was 9.0. The observed large slip is localized in the shallow Off-Miyagi, amounting to 60m [GSI, 2011]. The tsunami deposit surveys suggest this giant earthquake has a long recurrence time of 400-800 years [Sawai et al., 2010]. In the rupture area (megathrust area), there have been observed Mw7-class earthquakes, at least before the giant earthquake. The deep Off-Miyagi region had Mw7-class earthquakes with a recurrence interval of 30 - 40 years [Yamanaka and Kikuchi, 2004]. In Off-Ibaraki, Mw7-class earthquakes have recurred at intervals of about 28 years. The slip deficit maps show the decrease of the deficit rate in Off-Fukushima, just before the giant earthquake [GSI, 2011]. Some researchers consider this decrease may indicate the preparation just before the giant earthquake.

For this Tohoku earthquake, some cycle models have been proposed. Hierarchical asperity (HA) model [Hori and Miyazaki, 2011] set the whole megathrust area possesses the potential of generating earthquake. Kato and Yoshida [2011] considered the standard asperity (SA) model in 2D fault model. They set a strongly coupling asperity in the shallow area and other Mw7-class asperities surrounded by the stable sliding regions. Both models can reproduce the giant earthquake with a long interval and a large slip. The difference is the frictional state of the megathrust area. In this study, we perform the quasi-dynamic earthquake cycle simulations for HA and SA models, respectively.

For calculation, we use the 3D plate surface [Baba et al., 2006] as the fault. We subdivide it into 200,704 subfaults. We solve the simultaneous equations of motion and friction with adaptive time-step 5th Runge-Kutta [Press et al., 1996]. For the friction, we use the composite rate- and state- friction low [Kato and Tullis, 2001]. At each subfault, we set frictional parameters A, B, and L. For the fast computation, we use the H-matrices approximation method [Ohtani et al., 2011].

In both models, we set the frictionally unstable A-B<0 asperities in the deep Off-Miyagi and the Off-Ibaraki regions. We also set a strongly coupled asperity with A-B=-0.8 - -0.95MPa in the shallow Off-Miyagi region. In HA model, we set the whole megathrust area to be frictionally unstable with A-B<0. In SA model, we set the megathrust area with A-B>0, and an A-B<0 asperity in Off-Fukushima to reproduce the complex slip behavior. In this study, we consider the region only from Off-Miyagi to Off-Ibaraki.

In the results, both models could reproduce the characteristics of the Tohoku earthquake; the long recurrence time, the vast rupture area, and the localized large slip of the giant earthquake and the inside Mw7-class earthquakes with recurrence intervals of several decades. In both models, the localized large slip is due to the strongly coupled asperity. HA model can reproduce the long interval and the vast rupture area, even without the strong asperity. However, the large slip region broadens out in that case. Then, the strongly coupled region is required for slip localization.

After the afterslip of the giant earthquake, HA model shows the plate coupling at the whole megathrust area, while SA model gets to show the steady slip. This difference also makes the difference in the Mw7-class earthquake occurrences after the giant earthquake and in the plate coupling rate change in the interseismic period. Since the noticeable difference is seen after the giant earthquake, the further observation of the plate coupling will distinguish these models.

In our results, repeated slow slips occur in Off-Fukushima. The slow slips may be the cause of observed slip deficit decrease. They occur repeatedly, because the giant earthquake does not occur till the strongly coupled asperity is enough stressed. Thus, in both models, the occurrence of the slow slip does not indicate the preparation just before the giant earthquake.

Keywords: Tohoku earthquake, cycle, Off-Fukushima