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

SSS39-01 Room:IC Time:May 25 09:00-09:15

Atmospheric pressure waves from the 2011 great off-Tohoku earthquake (Mw=9.0)

MIKUMO, Takeshi[1*], Milton Garces[2], SHIBUTANI, Takuo[3], Wataru Morii[4], Takashi Okawa[5], ISHIHARA, Yasushi[6]

[1]Kyoto University, [2]Infrasound Lab., University of Hawaii, [3]DPRI, Kyoto University, [4]DPRI, Kyoto University, [5]Seismological Observatory, JMA, [6]IFREE, JAMSTEC

Atmospheric pressure waves were recorded within several hours after the great off-Tohoku earthquake by sensitive micro-barographs not only at several stations on and around the Japanese Islands, but also at 9 International Monitoring System (IMS) stations in the distance range between 1,000 and 6,500 km. Some of the near-field observations have been interpreted as non-dispersive boundary waves propagated along the bottom boundary of the atmosphere (Arai, et al.,2011). In addition to these, characteristic waveforms with two strong pulses can be identified at 3 other Japanese near-field stations, which are supposed to come from two stages separated within several minutes in tectonic vertical deformation on the sea-floor. The far-field observations including those at stations in Alaska, Hawaii, Palau, Australia, Far East Russia, Mongolia, Central Asia, and Greenland, indicate weak dispersive wave trains involving low frequencies between 1.5 and 3.3 mHz (or periods from 11 to 5 min) with a group velocity between 346 and 376 m/s and amplitudes ranging between 0.5 to 3 Pa, depending on their locations. For these reasons, these low-frequency waves may be interpreted as acoustic-gravity waves excited by swelling and depression of the sea surface due to vertical sea-floor deformation, and propagating through the lower to middle atmosphere, as in the cases of the 1964 Alaskan and 2004 Sumatra-Andaman earthquakes. Assuming various source parameters, we calculate synthetic waveforms for several far-field stations by incorporating a realistic, standard thermal structure in the atmosphere up to an altitude of 220 km, and then compare them with the corresponding observations. The comparison provides estimates of possible ranges for the effective source dimension generating these atmospheric pressure waves, average uplift and subsidence of the sea-floor and their time constants.

We expect that the results may become further information independent from seismic, geodetic, and tsunami observations, to the source characteristics of this great earthquake.

Keywords: 2011 off-Tohoku earthquake, Atmospheric pressure waves, near-field observations, far-field observations

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SSS39-02 Room:IC Time:May 25 09:15-09:30

The elastic rebound process of the 2011 great Tohoku-Oki earthquake

FUKAO, Yoshio[1*], Takane Hori[1], Shuichi Kodaira[1]

[1]IFREE/JAMSTEC

The 2011 Tohoku-Oki earthquake was an anomalously large elastic rebound of the upper-plate wedge against basal drag by the Pacific plate. The wedge consists of two parts, the seismically active inner (landward) segment and the inactive outer (oceanward) segment. A unique feature of this earthquake is the unexpectedly large rebound of the usually inactive outer segment. Here, we develop an elastic rebound model predicting a drastic change in stress state within the outer segment of the wedge characterized by a relatively steep seafloor and a very gentle plate interface. The model predicts, as the basal friction is reduced, the stress difference decreases in a horizontally compressional state, reaches a minimum (to which the stress state be referred) and then increases in a horizontally tensional state. The observed low seismic activity and normal fault-dominated seismic structure imply that the outer segment is in general marginally in a horizontally tensional state and decoupled from the compression-dominated inner segment by a strongly locked segment-segment boundary. The 2011 event started with unlocking of this boundary which shifted the area of stress concentration from the segment-segment boundary to the outer segment to place transiently the outer segment in a horizontally compressional state. The consequent large stress drop, accompanied by a drastic change of stress state within the outer segment, was transmitted to the inner segment through their already unlocked boundary. The unique role of the outer segment is a key to understand the whole rebound process of the Tohoku-Oki earthquake.

SSS39-03 Room:IC Time:May 25 09:30-09:45

Tidal triggering of earthquakes preceding the 2011 off the Pacific coast of Tohoku earthquake

TANAKA, Sachiko[1*], ASANO, Youichi[1]

[1]NIED

We observed tidal triggering of earthquakes preceding the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.1). We measured the statistical correlation between the Earth tide and earthquake occurrence in and around the rupture area of the Tohoku earthquake. The data we used are the centroid moment tensor (CMT) solutions of 2330 earthquakes with Mw 4.0 or larger from June 2003 to October 2011, which is reported by Asano et al. (2011). For each earthquake, we theoretically calculated tidal stresses on the fault plane (Tanaka et al., 2002); this calculation includes the direct solid Earth tide and the indirect term due to the ocean tide loading. Assigning the tidal phase angle at the occurrence time of each earthquake, we tested whether they concentrate near some particular angle or not by using the Schuster's test. In this test, the result is evaluated by p-value, which represents the significance level to reject the null hypothesis that the earthquakes occur randomly irrespective of the tidal phase angle.

Considering the shear stresses in the slip direction, we examined the spatial distribution of p-value before the Tohoku earthquake. As a result of analysis, we found no significant correlation. Changing the threshold magnitude of the data set, however, we observed small p-values in the nortern part of the mainshock source region. The smallest p-value of 0.19% is obtained in the 200 km square region (hereafter this region is referred to as region A), which includes the epicenter of the Tohoku mainshock, for the threshold magnitude of 4.8. The phase distribution in this case shows a peak near the angle 0, where the tidal shear stress is at its maximum to accelerate the fault slip. The temporal variation of p-value in region A shows that the p-value had been smaller than 5% over about a decade before the Tohoku earthquake. It gradually decreased with time, which lasted to the mainshock occurrence. After the Tohoku earthquake, the p-value was large (50%), indicating absence of significant correlation in this period.

We also observed similar space-time patterns of p-value when restricting our analysis to interplate earthquakes, which were identified following the method of Asano et al. (2011). However, the resultant p-value in the pre-mainshock period tends to be smaller than that observed for the data including all earthquakes. The p-value in region A is 0.08% for the threshold magnitude of 4.8.

Focusing on interplate earthquakes, we also try to evaluate the effects of fault-normal and Coulomb failure stresses. The data used for this analysis are the events with Mw 4.8 or larger that occurred in region A before the Tohoku earthquake. For these events, we assumed the west-dipping nodal planes as the fault planes. The p-value for normal stresses is 1.1%, which is larger than that for shear stresses, and a clear increase in the rate of events is found during times of compressional stresses inhibiting fault slip. We also examined Coulomb failure stresses giving different values of friction coefficient. A smaller p-value is obtained for a smaller friction coefficient, and the best correlation is for friction coefficient of 0 (shear stress only). This implies that shear stresses could play a dominant role on earthquake triggering in this region.

Keywords: the 2011 off the Pacific coast of Tohoku earthquake, earth tide, earthquake triggering, precursor

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SSS39-04 Room:IC Time:May 25 09:45-10:00

Seismic image of coseismic fault extending from the hypocenter to the trench axis by the 2011 Tohoku-oki earthquake

KODAIRA, Shuichi[1*], NO, Tetsuo[1], NAKAMURA, Yasuyuki[1], FUJIWARA, Toshiya[1], KAIHO, Yuka[1], TAKAHASHI, Narumi[1], KANEDA, Yoshiyuki[1]

[1]Japan Agency for Marine-Earth Science and Technology

The large tsunami followed the 2011 Tohoku-oki Earthquake is believed to be caused by a fault rupture extending from around 20 km deep at the plate boundary to a shallow part of the subduction zone at the Japan Trench, on the basis of seismic wave, tsunami and geodetic data. Those observations may indicate a need to revise a conceptual model of a subduction seismogenic zone which proposed a shallow part of subduction zone is aseismic slip zone. In order to examine a coseismic fault between the hypocenter and the trench axis, we processed seismic and bathymetry data acquired during a rapid response geophysical cruise soon after the earthquake, from 14th to 30th March in 2011, by using JAMSTEC R/V Kaire. From the seismic image, the plate interface can be traced down to around 20 km deep where the fault rupture was initiated. The angle of the plate interface seems to become low from the up-dip of the hypocenter at around 15 km deep. This variation of subduction angle is consistent with a seismic velocity image previously obtained by wide-angle OBS data. The seismic image of the up-dip end is characterized by a reflective zone slightly above the oceanic crust and a wedge-shaped structure which called a frontal prism. A weak reflector slightly above oceanic crust at the base of the frontal prism can be traced to the trench axis. In addition, comparing the seismic image of the trench-filled sediment obtained before and after the earthquake shows a seismological evidence of a co-seismic fault rupture extending along the plate boundary to the seafloor at the trench; i.e., the seismic image of the trench-filled sediment after the earthquake shows a compressional structure with several reverse faults branching from the master fault which reaches the trench axis. This result shows that a shallow part of a plate interface can be a seismic slip zone and that slip to the trench along the plate boundary is a cause of a large tsunami.

Keywords: Tohoku-oki eqrthquake, seismic image, fault, trench axis

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SSS39-05 Room:IC Time:May 25 10:00-10:15

Hypocenter distribution around the 2011 Tohoku-Oki earthquake by using Ocean Bottom Seismographic data

SUZUKI, Kensuke[1*], HINO Ryota[1], ITO Yoshihiro[1], YAMAMOTO Yojiro[2], SUZUKI Syuichi[1], Fujimoto Hiromi[1], SHINOHARA Masanao[3], ABE Masao[4], KAWAHARADA Yoshiharu[4], HASEGAWA Yohei[4], KANEDA Yoshiyuki[2]

[1]Tohoku University, [2]JAMSTEC, [3]ERI, University of Tokyo, [4]Japan Metrological Agency

A megathrust earthquake (M9.0), the 2011 off the Pacific coast of Tohoku earthquake (the 2011 Tohoku-Oki earthquake), occurred on Mar. 11, 2011 along the Japan Trench subduction zone. Its hypocenter and the area of major moment release are located in the Miyagi-Oki region, middle part of the Japan Trench area, where large interplate earthquake (~M7.5) have repeatedly occurred at about 40 years intervals. Since 2002, we have repeatedly deployed and retrieved pop-up type Ocean Bottom Seismometers (OBSs) to monitor the seismicity in the region. By this OBS network, we could observe a sequence of the foreshocks, the mainshock and aftershocks of the 2011 Tohoku-Oki earthquake in their close vicinity.

Suzuki et al. (2011) relocated these hypocenters by using OBSs data. Although OBSs deployed in the area observed the series of earthquakes and their data provided with improved image of the hypocenter distribution, they relocated only aftershocks with more than M-3.5 because vast number of earthquakes after the mainshock made it difficult to process the earthquakes with less than M-3.5. To investigate more detailed seismicity pattern, we relocated hypocenters of aftershocks with M-2.0~3.5 in addition to the their data set. In the first step of hypocenter determination, we calculated hypocenter positions by using 1D seismic velocity structure with applying station corrections for the OBS arrival time data and used those as the initial hypocenters in the second step. In the second step, we calculated hypocenters by using 3D seismic velocity structure estimated by Yamamoto et al. (2011) for a more detailed hypocenter determination.

The mainshock hypocenter was relocated slightly westward from that reported by JMA and near the intersection between the plate boundary and the Moho of the overriding plate. The foreshock seismicity mainly occurred on the trenchward side of the mainshock hypocenter, where the Pacific slab contacts the island arc crust. The foreshocks were initially activated at the up-dip limit of the seismogenic zone ~30 km trenchward of the largest foreshock (M 7.3, two days before the mainshock). After the M-7.3 earthquake, intense interplate seismicity accompanied by epicenters migrating toward the mainshock hypocenter was observed. The focal depth distribution changed drastically in response to the M-9 mainshock. Earthquakes along the plate boundary were almost extinct in the area of huge coseismic slip, whereas earthquakes off the boundary increased in population in both the upper and the lower plates.

Keywords: Tohoku-Oki earthquake, OBS, hypocenter distribution, foreshock, aftershock

SSS39-06 Room:IC Time:May 25 10:15-10:30

Finite element analysis for modeling the crustal deformation caused by the 2011 Tohoku-Oki earthquake

ITO, Yoshihiro[1*], SHIBAZAKI, Bunichiro[2], Kazuteru Garatani[3], HINO, Ryota[1], NAKAJIMA, Junichi[1]

[1]Graduate School of Science, Tohoku University, [2]Building Research Institute, [3]ITOCHU Techno-Solutions Corporation

We performed a finite element analysis for constructing a two-dimensional model of the deformation due to the 2011 Tohoku-Oki earthquake, taking into account the realistic subsurface structure and topography. We used a finite element code developed using GeoFEM. The two-dimensional cross section considered in the finite element analysis was perpendicular to the Japan Trench. This profile also transects an area of huge coseismic slip with the slip magnitude exceeding 60 m. Two-dimensional model of the crust, mantle wedge structures, and subducting slab geometry were developed on the basis of a offshore seismic reflection survey (Ito et al., 2005) and high-precision seismic tomography profile of the crust, mantle wedge structures, and subducting slab in this region (Nakajima et al., 2009). Rock density in each mesh is calculated from the P-wave velocity using the laboratory measurements of P-wave velocity and density reported by Ludwing et al. (1970). Assuming Vp/Vs ratios of 2.20, 1.90, 1.73, and 1.76 in the frontal prism, oceanic crust, continental crust, and mantle, respectively, we calculated their Poisson ratio and Young's modulus. First, we calculate the crustal deformation assuming an uniform slip model, following Ito et al. (2011). In this model, the updip of the fault reached the trench and the downdip was 80 km away from the trench; the slip magnitude was 80 m uniformly. The numerical results show an uplift of 8 m and a displacement of 75 m at a point 20 km away from the trench; however, the observed values of the uplift and displacement at this point were 5 m and 60 m, respectively. One of reasons of this discrepancy was the difference between fault geometries; Ito et al. (2011) considered simple fault geometry with a constant slope angle of 3^o, while our model adopts realistic curved fault geometry, taking into consideration the upper surface of the subducting plate. The other reason is the difference between the elasticity values of the frontal wedge and subducting plate; the vertical displacement increases by 10 percents near the trench if we assume homogeneous elasticity within the whole region. In future, we will develop a suitable model that can simulate crustal deformation consistent with the displacement as obtained by ocean-bottom as well as on-shore observations.

Keywords: The 2011 Tohoku-Oki earthquake, Finite element analysis, Ocean-bottom observation, Coseismic slip

SSS39-07 Room:IC Time:May 25 10:45-11:00

Tsunami source model of the largest foreshock on March 9th of the 2011 Tohoku-Oki earthquake

KUBOTA, Tatsuya[1*], INAZU, Daisuke[1], ITO, Yoshihiro[1], SUZUKI, Syuichi[1], SAITO, Tatsuhiko[2], SUZUKI, Kensuke[1], HINO, Ryota[1]

[1]Graduate School of Science, Tohoku University, [2]National Research Institute for Earth Science and Disaster Prevention

We calculated the fault model of the largest foreshock (Mjma 7.3) on March 9th of the 2011 Tohoku-Oki earthquake. When the foreshock occurred, we installed eight ocean bottom pressure gauges (OBPs) around the epicenter, which mainly recorded the tsunami and the seafloor deformation. The observed tsunami amplitudes and amounts of seafloor vertical movements were up to 15 cm and 10 cm, respectively. Since the location of the foreshock was close to the hypocenter of the M-9 mainshock, an estimation of the spatial extent of the foreshock rupture must be important to understand the generation process of the Tohoku earthquake.

We assumed a planer rectangle fault with constant slip and sought the tsunami source model explaining the waveforms observed by our OBPs. As a result of preliminary forward modeling, a pure reverse faulting in a rectangle of 30 x 50 km along the plate boundary explained the observed waveforms reasonably well. The location of the fault almost coincides with the large coseismic slip area estimated by seismic observations (Shao et al., 2011, GRL). The amount of slip of our source model is 1.4 m, and the seismic moment of our tsunami source model is 8.3 x 10^{19} Nm, equivalent to Mw 7.2.

We will estimate the fault model from tsunami waveform inversion, and compare it with the rectangle fault plane.

Keywords: Tsunami, The 2011 off the Pacific coast of Tohoku earthquake, Fault model, Ocean bottom pressurre gauges, The largest foreshock

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SSS39-08 Room:IC Time:May 25 13:45-14:00

Tomography of the Northeast Japan arc and mechanism of the 2011 Tohoku-oki earthquake sequence

ZHAO, Dapeng[1*]

[1]Department of Geophysics, Tohoku University

We have investigated the detailed 3-D seismic structure of the crust and upper mantle under the NE Japan arc and its implications for the mechanism of the 2011 Tohoku-oki earthquake (Mw 9.0) sequence. Significant structural heterogeneities are revealed in the interplate megathrust zone under the NE Japan forearc. Three low-velocity (low-V) anomalies exist off Sanriku, off Fukushima and off Ibaraki. There is a correlation between the velocity variation and the distribution of large thrust-type earthquakes (M ? 6.0) that occurred from 1900 to 2011, including the major foreshock, mainshock and aftershocks of the 2011 Tohoku-oki earthquake. The low-V patches in the megathrust zone may contain subducted sediments and fluids associated with slab dehydration, thus the subducting Pacific plate and the overriding continental plate may become weakly coupled or even decoupled in the low-V areas. In contrast, the high-velocity (high-V) patches in the megathrust zone may result from subducted oceanic ridges, seamounts and other topographic highs on the Pacific seafloor that become asperities where the subducting Pacific plate and the overriding continental plate are strongly coupled. Thus tectonic stress tends to accumulate in these high-V areas for a relatively long time during subduction, leading to the nucleation of large and great earthquakes in those areas. The off-Miyagi high-V zone, where the Tohoku-oki mainshock and its largest foreshock occurred, corresponds to the area with large coseismic slip (> 25 m) during the Tohoku-oki mainshock. This indicates that the off-Miyagi high-V zone is a large asperity (or a cluster of asperities) in the megathrust zone that ruptured during the Tohoku-oki mainshock.

High-resolution tomographic images of the crust and upper mantle in and around the area of the 2011 Iwaki earthquake (M 7.0) and the Fukushima nuclear power plant are determined by inverting a large number of high-quality arrival times with both the finite-frequency and ray tomography methods. The Iwaki earthquake and its aftershocks mainly occurred in a boundary zone with strong variations in seismic velocity and Poisson's ratio. Prominent low-velocity and high Poisson's ratio anomalies are revealed under the Iwaki source area and the Futaba fault zone, which may reflect fluids released from the dehydration of the subducting Pacific slab under NE Japan. The 2011 Tohoku-oki earthquake (Mw 9.0) caused static stress transfer in the overriding Okhotsk plate, resulting in the seismicity in the Iwaki source area that significantly increased immediately following the Tohoku-oki mainshock. This result suggests that the Iwaki earthquake was triggered by the ascending fluids from the Pacific slab dehydration and the stress variation induced by the Tohoku-oki mainshock. The similar structures under the Iwaki source area and the Futaba fault zone that is close to the Fukushima nuclear power plant suggest that the security of the nuclear power plant site should be strengthened to withstand potential large earthquakes in the future.

These results indicate that the rupture nucleations of the large events in the 2011 Tohoku-oki earthquake sequence, including the mainshock and major foreshocks and aftershocks, were controlled by the structural heterogeneities in the interplate megathrust zone and the over-riding continental plate.

Keywords: Great earthquakes, slab, fluids, active faults, seismic tomography

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SSS39-09 Room:IC Time:May 25 14:00-14:15

Initiation of the dynamic rupture of the 2011 Tohoku earthquake

UCHIDE, Takahiko[1*]

[1]DPRI, Kyoto University

The 2011 Tohoku earthquake (M 9.0) is characterized by a shallow huge slip more than 40 m, which produced the devastating tsunami. For modeling this earthquake, the stress accumulation and the kinematic rupture process should be understood. Here I focus on the kinematics of this earthquake in the early stage. A couple of studies already came out. Chu et al. (2011) found that the first 4 s of the rupture is equivalent to an Mw 4.9 thrust event. Uchide et al. (AGU, 2011) reported the source process in the first 20 s in detail by the multiscale slip inversion analysis (Uchide and Ide, 2007). Their result implies that rupture propagated eastward until 8 s, and after that the rupture propagated westward. The peak slip rate is around 1 m/s, which implies the dynamic rupture.

Hi-net data in Tohoku area shows that the velocity amplitude increases stepwise. Hi-net data are eventually clipped but they work at least in the first 20 s. The steps are found around 4 s and 16 s. In the first 1 s, the velocity amplitude of the M9 event is comparable to that of nearby M4 events (Mw 4.3 - 4.9). A deconvolution analysis using an M4 event (Mw 4.6 on Dec. 19, 2004 at 10:16 (UTC)) indicates a small event in the first 0.5 s.

I will also report the result of the multiscale slip inversion and the comparison of it to the seismicity between the M7.3 foreshock on March 9, 2011 and the mainshock (Ando and Imanishi, 2011).

Keywords: The 2011 Tohoku earthquake, Initial Rupture Process, Seismic Data Analysis, Multiscale Slip Inversion Analysis

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SSS39-10 Room:IC Time:May 25 14:15-14:30

Constraints on early stage rupture process of the 2011 Tohoku-oki earthquake from 1 Hz GPS data

FUKAHATA, Yukitoshi[1*], YAGI, Yuji[2], MIYAZAKI, Shin'ichi[3]

[1]Disaster Prevention Research Institute, Kyoto University, [2]Graduate School of Life and Environmental Sciences, University of Tsukuba, [3]Graduate school of Science, Kyoto University

From the comparison of observed 1 Hz GPS data with simple forward computation that evaluates near and intermediate field terms, we put constraints on the early stage rupture process of the 2011 Tohoku-oki earthquake. Mainly based on the time difference in the onset of large eastward displacements at stations along the northern coast of the source region, we estimated that the first significant moment release started around 35 km west of the hypocenter determined by JMA. The moment release continues about from 20 s to 35 s after the initiation of the earthquake. Significant moment release around the hypocenter and in the near-trench region starts from 25 s and 35 s at earliest, respectively. Clear opposite motion that follows large eastward displacement observed at many stations is due to the intermediate S-wave term.

Keywords: 2011 Tohoku-oki earthquake, 1 Hz GPS, rupture process, near field term, intermediate term

SSS39-11 Room:IC Time:May 25 14:30-14:45

Seismic Source Process of the 2011 Tohoku-oki Earthquake retrieved from tele-seismic body waveform

YAGI, Yuji[1*], NAKAO, Atsushi[1]

[1]Univ. of Tsukuba

Many researchers have performed source inversion using seismic waveforms observed at near-source or/and global seismic networks. As pointed out by some researchers, however, seismic source models for the 2011 Tohoku-oki earthquake are different from one another. The discrepancy has prevented us to understand the nature of mega-thrust earthquake in Tohoku-oki region. In this study, we compared seismic radiation area estimated by new back-projection method and fault slip distribution obtained by the new waveform inversion (Yagi and Fukahata, 2011), and then discussed the rupture process of the 2011 Tohoku-oki earthquake.

In general, back-projection images of shallow and thrust faulting earthquakes are contaminated by the reflected phase (e.g. pP and sP phase). In this study, we developed the back-projection method so as to use information of the reflected phases, and then applied it to tele-seismic body waveforms recorded on station of GSN and FDSN. Concretely, we project coross-correlating function between theoretical Green's function and observed waveform to seismic source region. The result obtained by the new method revealed that the result with the conventional back-projection is contaminated by the depth phases (Nakao and Yagi, 2012).

The estimated back-projection image is consistent with the rupture pattern by Yagi and Fukahata (2011) especially early episode, when projected wave sources slowly move both eastward and westward from the hypocenter. We also find high seismic energy released narrow area near trench after 35 - 50 sec from origin time where maximum slip is obtained by Yagi and Fukahata (2011). The high-energy event in huge slip area implied the continuous and large stress drop event occurred near trench, which may be explained by significant weakening of frictional strength on the fault plane.

Keywords: the 2011 Tohoku-oki Earthquake, Seismic Source Process, back-projection

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SSS39-12 Room:IC Time:May 25 14:45-15:00

Source model of the 2011 great Tohoku earthquake estimated from tsunami waveforms and crustal deformation data

GUSMAN, Aditya[1*], Yuichiro Tanioka[1], Shinichi Sakai[2], Hiroaki Tsushima[3]

[1]Institute of Seismology and Volcanology, Hokkaido University, [2]Earthquake Research Institute, University of Tokyo, [3]Meteorological Research Institute, Japan Meteorological Agency

The slip distribution of the 11 March 2011 Tohoku earthquake is inferred from tsunami waveforms, GPS data, and seafloor crustal deformation data. The major slip region extends all the way to the trench, and the large slip area extends 250 km long and 160 km wide. The largest slip of 44 m is located up-dip of the hypocenter. The large slip amount, about 41 m, ruptured the plate interface near the trench. The seismic moment calculated from the estimated slip distribution is 5.5 x 10^22 N m (Mw 9.1). The large tsunami due to the 2011 Tohoku earthquake is generated from those large slip areas near the trench. The additional uplift at the sedimentary wedge as suggested for the 1896 Sanriku earthquake may have occurred during the 2011 Tohoku earthquake, too.

Keywords: tsunami waveforms, GPS data, seafloor crustal deformation data, the 2011 Tohoku earthquake

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SSS39-13 Room:IC Time:May 25 15:00-15:15

Rupture process analysis of the 2011 Tohoku-Oki earthquake using 2.5D finite-difference Green's functions

OKAMOTO, Taro[1*], TAKENAKA, Hiroshi[2], HARA, Tatsuhiko[3]

[1]Tokyo Institute of Technology, [2]Kyushu University, [3]Building Research Institute

The March 11, 2011 Tohoku-Oki earthquake (GCMT Mw9.1) generated strong shaking reaching the maximum intensity (seven) on the JMA's scale and caused devastating tsunamis with run-up heights exceeding 30 m. Such ultra-large-sized earthquake of magnitude 9 was not expected to occur along the plate interface off the northeastern Japan. Thus it is very important to infer the rupture process of this event for understanding the geophysical condition of the generation of magnitude-9-class earthquake and the mechanism of the excitation of the large tsunamis.

We present the rupture process analysis of the 2011 Tohoku-Oki earthquake by using a non-linear teleseismic body waveform inversion method [1]. We incorporate the effect of the near-source laterally heterogeneous structure (including the ocean layer and sediments) on the waveforms by using a 2.5-dimensional finite difference method [2]. This is because the structural effect can leads to improper solutions if the effect is not considered (e.g., a flat layered structure is used) in generating the synthetic waveforms [1]. We use thirty one P-waveforms (vertical component of displacement) within the epicentral distance range from 30 degree to 90 degree. We remove the instrumental response from the raw-data and apply a bandpass-filter with corner frequencies of 0.2 Hz and 0.004 Hz (5 s to 250 s). The final sampling rate is 2 s.

The preliminary analysis by using the finite-difference Green's functions results in a heterogeneous rupture process with large slips off Miyagi prefecture, near and around the JMA epicenter. The maximum slip is about 45 m, and the moment magnitude is about 4.1e22 Nm (Mw 9.0). The results (large slips near the epicenter) is similar to that obtained by a joint inversion [3]. We will further discuss the differences in the solutions for different Green's functions: we will compare the results obtained by using the finite-difference Green's functions and those by using Green's functions computed for flat-layered near source structure model.

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Keywords: 2011 Tohoku-oki earthquake, rupture process, waveform inversion, teleseismic wave, 2.5D finite-difference

SSS39-14 Room:IC Time:May 25 15:30-15:45

Shallow high-frequency seismic radiation during the 2011 Tohoku-Oki earthquake, Japan

KUMAGAI, Hiroyuki[1*], PULIDO, Nelson[1], FUKUYAMA, Eiichi[1], AOI, Shin[1]

[1]NIED

The megathrust earthquake that struck the Tohoku region, Japan, on 11 March 2011 was observed by dense seismic networks. Strong-motion waveforms indicated that distinct sub-events occurred during the Tohoku-Oki earthquake. To investigate source processes of the earthquake, we utilized a source location method using high-frequency (5-10 Hz) seismic amplitudes, which enabled us to locate sources of continuous signals. We estimated source locations in successive time windows using strong-motion waveforms from the KiK-net. We detected three main sub-events during a total source duration of 100 s. The sources of these sub-events were at shallow depths near the Japan Trench, where few aftershocks occurred. Our estimated source area was south of the large slip area estimated from low-frequency seismic data. The first two sub-events were determined at very similar locations with an interval of 40 s. Repeated ruptures on the same fault are extremely unlikely, implying that an auxiliary fault may have been involved during the Tohoku-Oki earthquake. Our results imply a possibility that the first sub-event ruptured an auxiliary fault, perhaps the backstop interface, and triggered the second sub-event and the main rupture along the plate interface. The third sub-event ruptured south of the main slip area near the trench. Our study indicates repetitive triggering of multiple sub-events radiating high-frequency seismic waves at shallow depths during the Tohoku-Oki earthquake.

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SSS39-15 Room:IC Time:May 25 15:45-16:00

Source process analysis of the 2011 Tohoku earthquake using the 3-D Green's functions

YOKOTA, Yusuke[1*], KOKETSU, Kazuki[1]

[1]Earthquake Research Institute, University of Tokyo

The 2011 Tohoku earthquake occurred at 5:46 a.m. on March 11, 2011 (UTC). The Japan Meteorological Agency (JMA) estimated its moment magnitude (M_w) to be 9.0. This earthquake was observed by dense strong motion, teleseismic, geodetic, and tsunami networks. Various source models were inferred using these datasets. In the previous study, we performed a quadruple joint inversion using strong motion, teleseismic, geodetic, and tsunami datasets to determine a source model [*Yokota et al.*, 2011]. However, we calculated Green's functions using the 1-D velocity structure. In this study, we performed the strong motion inversion using Green's functions calculated using the 3-D velocity structure which reflected the subduction zone.

The 3-D Green's functions were calculated using the voxel finite element method (FEM) [*Koketsu et al.*, 2004; *Ikegami et al.*, 2008]. We used the 3-D velocity structure of JIVSM model [*Koketsu et al.*, 2008]. The obtained 3-D Green's functions involved the complex later phases compared to 1-D Green's functions calculated by the method of *Kohketsu* [1985]. We believe that these complex phases were caused by the surface waves generated in the plate boundary and ocean.

We then performed the strong motion inversion using the obtained 3-D Green's functions by means of the method of *Yoshida et al.* [1996] with the revisions of *Hikima and Koketsu* [2005]. There were some differences between the results obtained using the 1-D velocity structure and the 3-D velocity structure. We plan to carry out similar analyses for other datasets.

Acknowledgement:
Strong motion data were provided by K-NET and KiK-net strong motion network, we would like to thank them.

Keywords: 2011 Tohoku earthquake, source process, 3-D velocity structure, strong motion

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Dynamic overshoot near the trench caused by a large asperity breaking at depth

FUKUYAMA, Eiichi[1*], HOK, Sebastien[2]

[1]Nat'l Res. Inst. Earth Sci. Disas. Prev., [2]Ecole Normale Superieure de Paris

We investigated an earthquake generation model caused by subduction of a plate having a bumpy shaped interface geometry by a realistic numerical modeling of earthquake dynamic rupture. Bumpy shaped plate interfaces might be formed by subduction of old submarine volcanoes or seamounts. We assumed that during the inter-seismic period, slip only occurs outside the bump area and the stress is further accumulated inside the bump. Since we assumed a constant rate subduction as a long-term average, we could estimate roughly the amount of slip outside the bump during the inter-seismic period and then we could estimate the accumulated stress inside the bump. We constructed the initial stress distribution based on the stress change caused by the slip deficit distribution. We then constructed constitutive relations based on slip-weakening friction law. From the result of the computations, we found that large slip can occur between the free surface and the bump where very low stress is accumulated before the rupture. This is caused by the interaction between the free surface and the fault slip. At deeper side of the asperity, since the fault is sustained by the un-slipped zone, such slip overshoot never occurs. But at shallower side, when the rupture approaches the free surface, the fault becomes the un-sustained situation between the free surface and bump. In this region, such a large slip can occur without releasing large amount of stress. This idea could be applied for the interpretation of the 2011 Tohoku-Oki earthquake where large amount of slip were observed at shallow depth near the trench.

Keywords: Dynamic rupture, Slip overshoot, Bumpy fault

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A mechanical scenario for the occurrence of the Tohoku earthquake: stress concentration and thermal fluid pressurization

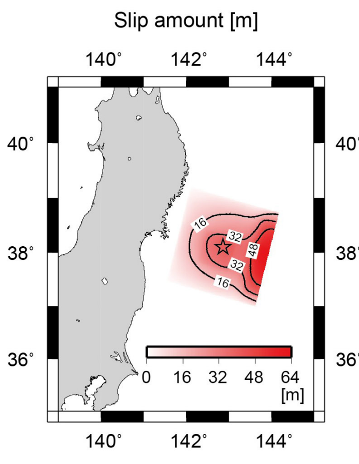
MITSUI, Yuta[1*], IIO, Yoshihisa[2], FUKAHATA, Yukitoshi[2]

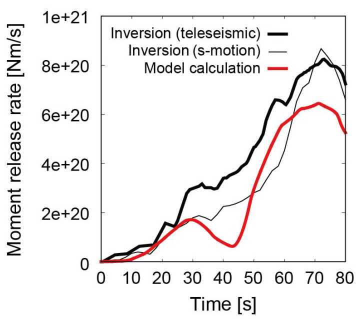
[1]Sci. Hokkaido Univ., [2]DPRI, Kyoto Univ.

As a preliminary result, Mitsui and Iio (2011, EPS) proposed a scenario of the generation mechanism of the 2011 Tohoku earthquake on March 11, referring to geophysical observation data; the M7-class earthquake, which had occurred on March 9 after the active period of M7-class earthquakes and afterslip, might trigger the M9 Tohoku Earthquake through its afterslip. Similar scenarios had been also presented by several researches. Mitsui and Iio also implied that some mechanisms, such as thermal pressurization of pore fluid (TP) on the fault plane, caused extremely large slip in the northern part of the M9 fault to propagate the seismic rupture over the whole fault. On the basis of this way of thinking, Mitsui et al. (accepted, EPSL) modeled an M9 earthquake cycle, including M7-class earthquakes, with the TP mechanism near the trench. Although several different models for the generation process of the Tohoku earthquake had been proposed, our concept provides a good explanation for the occurrence of the Tohoku earthquake.

Moreover, here, we perform dynamic rupture simulations for better understanding the generation process of the 2011 Tohoku earthquake. We construct a fault model to assimilate the moment release in the seismic slip inversions. It also reflects the estimation of shear stress changes before the Tohoku earthquake, due to the four M7-class earthquakes during 2003-2011 (Iio and Matsuzawa, submitted). We assume a dynamic weakening mechanism of TP to represent nonlinear weakening friction. The simulation result implies the following things about the 2011 Tohoku earthquake. (1) The rupture around the hypocenter was enhanced by the stress accumulation due to the preceding M7-class earthquakes. (2) The enhanced rupture triggered the TP mechanism in the near-trench area to cause nearly total stress release, which promoted the rupture throughout a wide region including the source areas of the M7-class earthquakes and a surrounding conditionally stable area. (3) Without sufficient stress accumulation, the moment release of the Tohoku earthquake ended as an M8-class earthquake. (4) TP in the near-trench area should be effective but moderate (depending on the size of the TP area).

Keywords: The 2011 Tohoku earthquake, thermal fluid pressurization, stress concentration, dynamic rupture simulation





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3D modeling of the cycle of a Tohoku-oki earthquake considering high-velocity friction: preceding and postseismic slips

SHIBAZAKI, Bunichiro[1]*, TSUTSUMI, Akito[2], UJIIE, Kohtaro[3], SHIMAMOTO, Toshihiko[4], ITO, Yoshihiro[5]

[1]IISEE, Building Research Institute, [2]Kyoto University, [3]University of Tsukuba, [4]China Earthquake Administration, [5]Tohoku University

The preceding, coseismic, and postseismic slips of the 2011 Tohoku-oki earthquake were investigated in detail by several authors. Suito et al. (2011) reported that preceding aseismic slips began occurring in the off Miyagi to off Ibaraki region in 2004, along with M7-class earthquakes. After the 2011 Tohoku-oki earthquake, postseismic slips occurred in an area where coseismic slips were not significant (Ozawa et al., 2012). The occurrences of preceding, coseismic and postseismic slips are controlled by friction properties. The present study investigates preceding and postseismic slips, by using the model developed by Shibazaki et al. (2011). They performed 3D quasi-dynamic modeling of the cycle of a megathrust earthquake in the offshore Tohoku region, Japan, using a rate- and state-dependent friction law with two state variables that exhibits strong velocity weakening at high slip velocities. They set several asperities where velocity weakening occurred at low to intermediate slip velocities. Outside the asperities, velocity strengthening occurred at low to intermediate slip velocities. At high slip velocities, strong velocity weakening with large displacements occurred both within and outside the asperities.

The results of numerical simulations showed that, before the occurrence of M9 class events, M7.5 class earthquakes occurred in the off Miyagi, Fukushima, and Ibaraki regions. Slip velocities increased significantly in the region surrounding strong asperities. M9 class earthquakes initiated around the strong asperities. Following the main event, postseismic slips occurred at the deeper part of the seismogenic zone. In the region that is located below the northern shallow rupture area of the simulated Tohoku-oki earthquake, large postseismic slips occurred. In the off Miyagi region, postseismic slips occurred in the deep area where coseismic slip was small. On the other hand, in the off Fukushima and off Ibaraki regions, small postseismic slips occurred in the region between asperities. The distribution of postseismic slips obtained by our simulation is roughly consistent with the observed actual distribution (Ozawa et al., 2012). In the present model, we set the velocity-strengthening region in the off Ibaraki region close to the Japan Trench. Therefore, significant postseismic slips occurred in the off Ibaraki region close to the trench. If the frictional property in this region is stable, large postseismic slips will be detected by the observation of ocean bottom crustal deformation.

Keywords: the 2011 Tohoku-oki earthquake, 3D earthquake cycle model, high-velocity friction, preceding slip, postseismic slip

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Identification and simulation of seismic supercycles along the Japan Trench including the 2011 Tohoku earthquake

KOKETSU, Kazuki[1*], YOKOTA, Yusuke[1], KATO, Naoyuki[1], KATO, Teruyuki[1]

[1]Earthquake Research Institute, University of Tokyo

The devastating Tohoku earthquake of magnitude (M) 9.0 occurred on 11 March 2011 UTC along the Japan Trench, where the Pacific plate is subducting beneath the Tohoku district. The national program of seismic hazard assessment, which was initiated by the Japanese government after the 1995 Kobe earthquake, failed to foresee this earthquake, because no supercycle of megathrust events had been identified along the Japan Trench. For example, the program identified a normal cycle of six M7 to 8 earthquakes in the land side of the Miyagi-oki region, and only reported the high probability of having another M7 earthquake there.

The Japanese government also built nation-wide dense arrays of seismometers and GPS receivers after the Kobe earthquake. We have recovered annual rates of back slip, which is the drag of the overriding plate by interplate coupling, using GPS data during a calm period before the Tohoku earthquake. We then recovered coseismic slips through a inversion of GPS data during the earthquake. The distributions of recovered coseismic slips and back slip rates bear a close resemblance to each other. An area of large back slip rate was previously thought to be related to a normal cycle of M7 to 8 earthquakes. However, our result demonstrates that the area is related to a supercycle of megathrust earthquakes.

From the coseismic slips and back slip rates in the Miyagi-oki region, we calculated the coseismic moment release and moment accumulation rate of the Tohoku earthquake to 15 x 10**21 Nm and 0.04 x 10**21 Nm/year, respectively. Since normal earthquakes occasionally release some part of accumulated seismic moment, those in the Miyagi-oki region were compiled. We then calculated the moment releases by them to be 5 x 10**21 Nm. These moment releases and accumulation rate lead to a supercycle period of about 500 years. However, this period is too short, if the 869 Jogan earthquake is the only documented event to have occurred with a possible magnitude and location similar to that of the Tohoku earthquake. Within the compilation,

the 1611 Keicho earthquake can be a hidden candidate between the 869 Jogan and 2011 Tohoku earthquakes. Extensive tsunami damage caused by this earthquake was documented over the Tohoku district. The time series, which was drawn using the moment releases and accumulation rate, is mostly controlled by the moment releases of megathrust earthquakes.

We next conducted a numerical simulation of the seismic supercycles and normal earthquake cycles identified above. A strong patch (asperity) with higher effective normal stress and a large value of characteristic slip distance is assumed at a shallower part of the plate interface. This strong patch controls the occurrence of megathrust earthquakes that broke the entire seismogenic plate interface with recurrence intervals of several hundred years. The present model explains coseismic slips at a shallower part of the Tohoku earthquake and back slip rates at deeper parts, where normal events repeatedly occurred before the earthquake.

Keywords: Tohoku earthquake, megathrust earthquake, supercycle, simulation, back slip