Coseismic slip distribution of the 2011 off the Pacific coast of Tohoku Earthquake (*M* 9.0) estimated based on GPS data— Was the asperity in Miyagi-oki ruptured?

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(Received April 19, 2011; Revised June 1, 2011; Accepted June 8, 2011; Online published September 27, 2011)

We investigated the crustal deformation associated with the 2011 off the Pacific coast of Tohoku Earthquake (*M* 9.0) that occurred on March 11, 2011, along the plate boundary off Tohoku district, northeastern Japan, based on dense GPS observation. Coseismic displacements due to this event were applied to estimate the causal interplate slip by means of a geodetic inversion analysis. The major slip area is located around the asperities of the 1981 Miyagi-oki (*M* 7.2) and 2003 Fukushima-oki (*M* 6.8) earthquakes and the maximum slip is estimated as being up to 35 m. The estimated slip distribution suggests that the asperities of the Miyagi-oki earthquake in 1978 (*M* 7.4) that had not been ruptured during the Miyagi-oki earthquake in 2005 were ruptured as a part of the main shock fault of the 2011 off the Pacific coast of Tohoku Earthquake.

Key words: 2011 off the Pacific coast of Tohoku Earthquake, interplate earthquake, GPS, slip distribution, Miyagi-oki earthquake.

1. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake (*M* 9.0) occurred on 11 March, 2011, off the Pacific coast of Tohoku district, northeastern Japan, where the Pacific plate is subducting at a rate of about 70∼85 mm/year beneath the overriding continental plate (Altamimi *et al.*, 2007). The plate interface between the Pacific and the overriding continental plates around the Tohoku district is one of the most active areas of seismicity in the world. Various studies of major interplate earthquakes around this area have revealed that some of those events can be regarded as recurrent ruptures of asperities, which are defined by distributed patches showing large coseisimc slip (e.g., Nagai *et al.*, 2001; Yamanaka, 2003; Yamanaka and Kikuchi, 2003, 2004). The rupture area of the 2011 Tohoku Earthquake includes several asperities of $M \sim 7$ earthquakes offshore of Ibaraki-Fukushima-Miyagi-Iwate prefectures according to preliminary results of seismological and geodetic data analyses (e.g., Ito *et al.*, 2011; Yagi and Nishimura, 2011; Yamanaka, 2011; Tobita *et al.*, 2011)

Earthquakes with magnitudes of about 7.4 ∼ 7.5 have repeatedly occurred on the plate boundary east of Miyagi prefecture (Miyagi-oki) with an interval of about 37 years. The most recent one took place in 1978, i.e., the *M* 7.4 Miyagi-oki earthquake (e.g., Seno *et al.*, 1980; Umino *et al.*, 2006). Based on historical records of these recurrent earthquakes, the Headquarters for Earthquake Research Promotion (2011) stated that the next Miyagi-oki earthquake will occur with a probability of about 70% in the next 10 years from 1 January, 2011.

On August 16, 2005, there occurred an interplate earthquake with magnitude 7.2, hereafter referred to as the 2005 Miyagi-oki earthquake. Okada *et al.* (2005) carried out the relocation of aftershocks of the 1978 and 2005 events to reveal that the aftershock area of the 2005 event overlaps only with the southeastern part of the 1978 source area. Yaginuma *et al.* (2006) performed seismic waveform inversion for the 2005 event to estimate the coseismic slip distribution and found that it also corresponds to the southeastern part of the 1978 rupture area. The northern and southwestern parts of the rupture area of 1978 earthquake did not slip aseismically after the 2005 earthquake (Miura *et al.*, 2006; Iinuma *et al.*, 2011). Therefore, it was considered that the remaining asperities of the 1978 Miyagi-oki earthquake had not been ruptured and had been accumulating strain energy since 1978 for the next Miyagi-oki earthquake, until the 2011 earthquake occurred.

Here, we consider the problem as to whether the remaining asperities of the 1978 Miyagi-oki earthquake ruptured with the 2011 off the Pacific coast of Tohoku Earthquake, or not, based on land GPS observation data. In the present study, we use GPS data to estimate coseismic slip distributions on the plate boundary by means of a geodetic inversion method.

2. Data and Analysis

Tohoku University has been conducting continuous GPS observations in the Tohoku district since 1987 (Miura *et*

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doi:10.5047/eps.2011.06.013

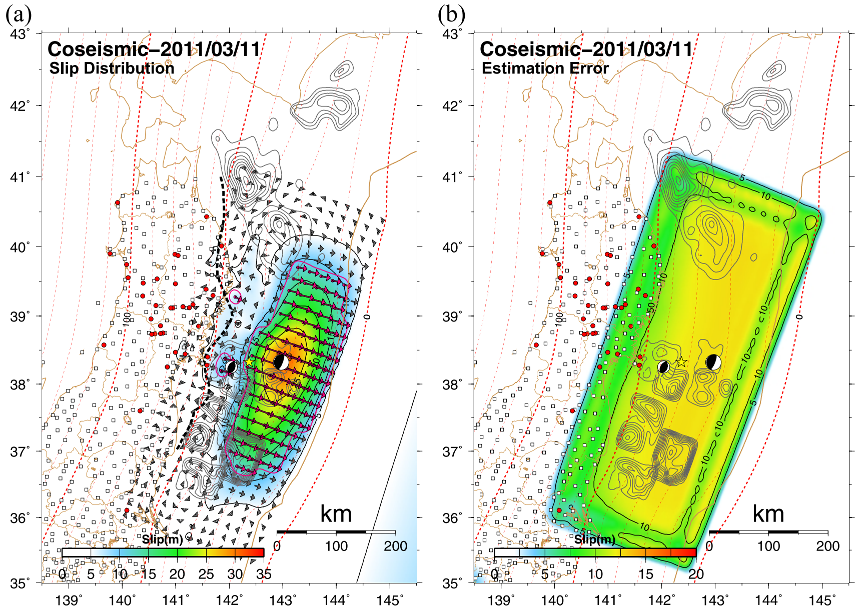

Fig. 1. (a) Coseismic slip distribution estimated from observed displacements at all GPS stations. Arrows denote slip vectors on the hanging wall of the plate interface. Contours of the interplate slip are also shown with a color scale. The contour interval is 5 m. Purple arrows and the areas surrounded by the purple solid lines indicate that here the estimated values are greater than the estimation errors. White squares and red circles denote GPS stations conducted by the GSI and Tohoku University, respectively. The black dashed line denotes down-dip limit of interplate earthquakes determined by Igarashi *et al.* (2001). The broken red lines show the depth of the subducting plate interface. The epicenter of the main shock and mechanism solutions of the main shock and an aftershock on 7 April, 2011, (M 7.1) estimated based on W-phase inversion analysis are indicated by a yellow star and the beach-ball symbols (USGS, 2011a, b). The gray contours denote the slip areas for recent major earthquakes at Tokachi-oki in 2003 (Yamanaka and Kikuchi, 2003) and 1968, Miyagi-oki in 1978, 1981 and 1936 (Yamanaka and Kikuchi, 2004), Fukushima-oki in 2003 (Yamanaka, 2003) and 1938 (Murotani, 2003). The thin brown lines denote the prefectural borders. (b) Estimation error distribution. The contour interval is 5 m.

al., 1993). The GPS observation network of Tohoku University spatially interpolates the nationwide GPS network, GEONET, which is managed by the Geospatial Information Authority of Japan (GSI). We can improve the spatial resolution of the inversion analysis to estimate the coseismic slip distribution especially around the Miyagi-oki region by using GPS data observed at 383 sites of not only GSI (345 sites) but also Tohoku University (38 sites). Ohzono *et al.* (2011) estimated the site coordinates before and after the mainshock by using Bernese GPS Software version 5.0 (Dach *et al.*, 2007), and calculated coseismic displacements by taking the differences between the daily site coordinates of before and after the mainshock, namely on March 10 and 11 (after 5:47 on GPS time). Refer to Ohzono *et al.* (2011) for further details of GPS observation and data processing.

We estimated the coseismic slip distribution based on the displacement field determined by Ohzono *et al.* (2011), using an inversion method proposed by Iinuma (2009). In this inversion method, the weights of three constraint conditions, namely, spatial smoothing, initial value damping, and the boundary condition are optimized by minimizing Akaike's Bayesian Information Criterion (ABIC) (Akaike, 1977, 1980). We applied a plate-boundary model estimated by Nakajima and Hasegawa (2006) to model the plate interface fault. Vertical and horizontal displacements are equally weighted in the inversion analysis, because the modeling errors due to the uncertainty and heterogeneity of the physical properties of the crust, such as rigidity and Poisson's ratio, the error of the geometry of the plate-interface fault, the effect of the terrain topography, and so on, must exceed the observation errors at most GPS stations.

3. Results and Discussion

Estimated slip vectors on the hanging wall of the plate interface are shown by arrows and contours with an interval of 5 m in Fig. 1. The coseismic slip is centered around the moment tensor solution based on W-phase analysis performed by the US Geological Survey (USGS) (2011a) denoted by a beach-ball symbol. Looking at the area of major slip shown by the contour of 30 m, it overlaps the asperities of the 1981 Miyagi-oki earthquake (Yamanaka and Kikuchi, 2004) and the 2003 Fukushima-oki earthquake (Yamanaka, 2003). The total seismic moment obtained by integrating the distributed slip shown in Fig. 1 amounts to 4.0×10^{22} N m, which is equivalent to a moment magnitude of 9.0 and almost identical with the value determined by the Japan Meteorological Agency (JMA) (2011a).

The area of significant slip, where the slip is larger than the estimation error (surrounded by purple lines in Fig. 1), is divided into two areas. One is the main rupture area on the plate interface shallower than 30 km in depth, where the subducting plate is in contact with the crust of the continental plate. Another is located at the Miyagi-oki region where the asperities that caused the 1978 Miyagi-oki earthquake are distributed. The hanging-wall side of the plate-interface fault is the continental mantle at the Miyagi-oki region. We can conclude that tremendous slip in the crust-crust contact zone on the plate boundary mainly caused the 2011 off the Pacific coast of Tohoku Earthquake, and that the boundary between the continental crust and the mantle on the hanging-wall side of the plate interface fault might

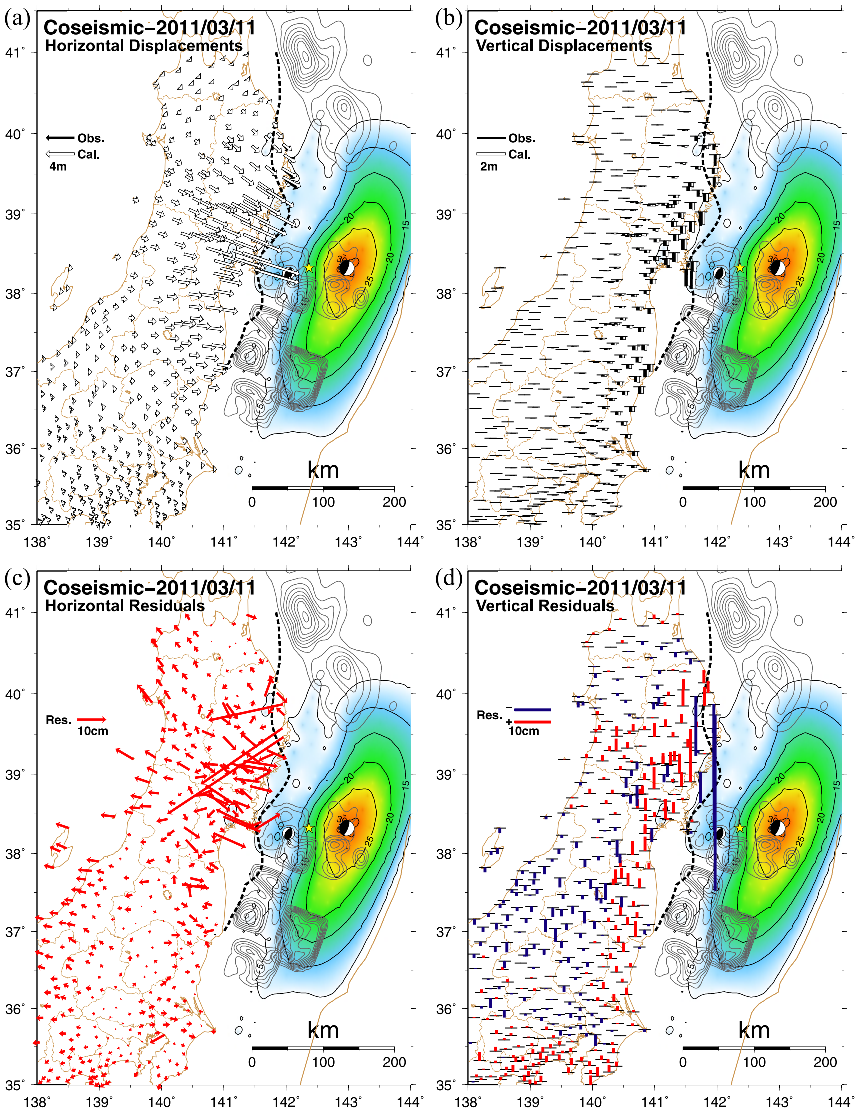

Fig. 2. Comparison between observed displacements (black arrows in (a) and bars in (b)) and calculated ones (white arrows in (a) and bars in (b)) from the estimated coseismic slip distribution. (a) Horizontal component and (b) vertical component are shown with their residuals ((c) and (d)). The residuals are calculated by subtracting the calculated displacement from the observed displacement for each site.

prevent the main-shock rupture from propagating into the crust-mantle contact zone along the plate interface. Miyagi-oki, however, is an exceptional region where coseismic slip also has occurred on the plate interface under the continental mantle. The heterogeneity of the mantle wedge might control this slip heterogeneity in the crust-mantle contact zone as Yamamoto *et al.* (2008) suggested. Yamamoto *et al.* (2008) found that the mantle wedge above the coseismic slip area of the 1978 Miyagi-oki earthquakes is characterized by high V_p and V_s, but low V_p/V_s, which they interpreted as indicating a less-serpentinized state, while V_p/V_s is high at the updip end of the mantle wedge in the Fukushima-oki region possibly because of extensive serpentinization. Therefore, the elastic-strain energy can be accumulated in the asperities in the Miyagi-oki region, and is released by causing seismic slip.

Slip up to 15 m is estimated around the western and northern asperities of the Miyagi-oki earthquake in 1978, and the estimated values in this region are greater than the estimation error. This result indicates that the remaining asperities of the Miyagi-oki earthquake were ruptured with the occurrence of the 2011 off the Pacific coast of Tohoku Earthquake. However, the slip amount is too large to be accounted solely by the cumulative slip deficit since 1978, if the slip deficit was reduced to zero by the 1978 earthquake. The cumulative slip deficit should be no more than 3 m, because the plate convergence rate (70∼85 mm/year) times the lapse time since the 1978 Miyagi-oki earthquake (about 33 years) is equal to about 2.3∼2.8 m even if the plate interface is fully coupled during the whole interseismic period. Further investigation is therefore required to balance the budget of slip and slip deficit.

The estimated slip distribution suggests that the main shock rupture did not propagate into the brittle-ductile transition zone along the plate interface. Igarashi *et al.* (2001) pointed out that there is a clear boundary of the distribution of the interplate earthquakes in this region, which is indicated by the dashed line in all figures in this paper, and no slip is estimated at the plate interface deeper than this border. However, weak interplate coupling has been estimated

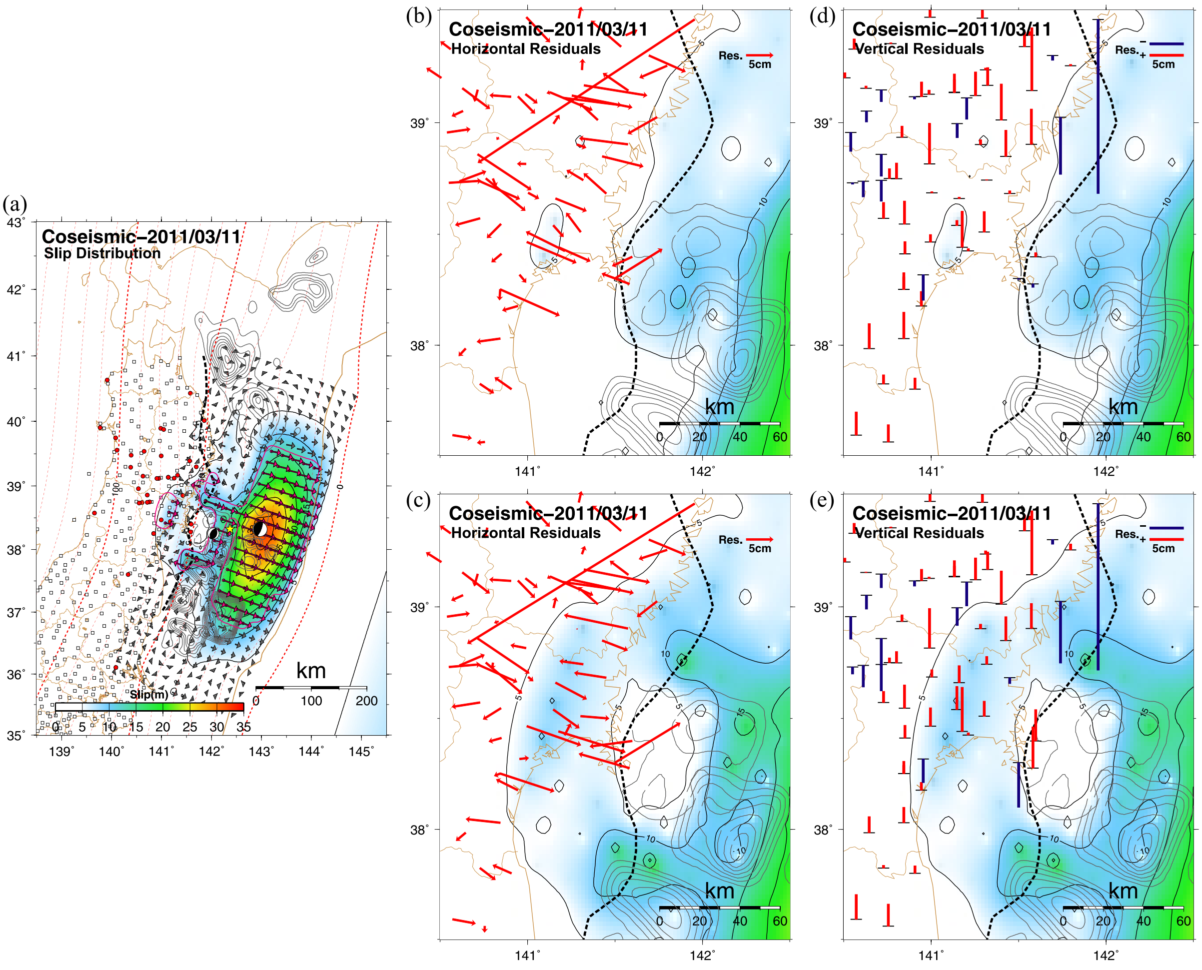

Fig. 3. The results when we imposed an additional condition that the slip in the Miyagi-oki region is constrained to be zero, and the comparison of the residuals between the optimum and the constrained models. (a) Coseismic slip distribution is presented as in Fig. 1(a). The distributions of the residuals of the horizontal components ((b) and (c)) and of vertical displacements ((d) and (e)) around the Miyagi-oki region are displayed. The residuals are calculated by subtracting the calculated displacement from the observed displacement for each site. The results based on the optimum model are shown in (b) and (d). (c) and (e) represent the results based on the constrained model.

in the deeper plate boundary based on interseismic crustal deformation data (e.g., Ito *et al.*, 2000; Nishimura *et al.*, 2004; Suwa *et al.*, 2006). Thus, postseismic slip is expected to occur in the plate interface deeper than this boundary in order to release the cumulative strain energy due to the interplate coupling.

An *M* 7.1 aftershock occurred on 7 April, 2011, in the Miyagi-oki region, near the rupture area of the Miyagi-oki earthquake in 1978 (see Fig. 1). This aftershock, however, must have occurred in the subducting Pacific slab according to the moment tensor analyses (USGS, 2011b; JMA, 2011b) and to an analysis of the crustal deformation (Ohta *et al.*, 2011). The epicenter of this aftershock is located in the low slip area between the main rupture area and the rupture area in Miyagi-oki. This heterogeneity of slip distribution may have caused this aftershock due to the stress concentration (Yoshida, personal communication).

We performed another geodetic inversion analysis constraining the slip in the Miyagi-oki region to be zero. The result is shown in Fig. 3. Since the slip in the Miyagi-oki region is excluded, significant slip is estimated in the areas surrounding the Miyagi-oki region, while the main rupture area on the shallow plate interface is almost identical. We can obtain a slip distribution entirely identical to the slip distribution of the optimum model with an ABIC value of -83134 by using the very small ($<10^{-17}$) hyperparameter that proportionally controls the weight of the additional constraint condition, while the ABIC is calculated to be -81770 for the constrained model in which the hyperparameter is 1.0. We can conclude that, based on the ABIC values, the model with no additional constraint conditions is better than the constrained model.

Figure 3 presents the comparison of the residual distributions between the results of the optimum and the constrained models. Both horizontal and vertical components of the residuals increase at the sites near the asperity of the 1978 Miyagi-oki earthquake when the additional constraint condition is imposed. In particular, the residuals of vertical displacements are greater than 5 cm at three sites that are closest to the Miyagi-oki asperities. Two of these three sites are not GSI's, but Tohoku University's, GPS stations (see Fig. 1). It clearly emphasises that the coseismic large slip in the Miyagi-oki region is essential to explain the observed displacement, and that the high density of the GPS observation array is necessary to estimate the precise slip distribution in the spatial resolution of 20∼40 km on the deep (>30 km) plate interface around Miyagi-oki region.

4. Summary

Coseismic deformations associated with the 2011 off the Pacific coast of Tohoku Earthquake were investigated to resolve the causal interplate slips using a dense GPS array data and the geodetic inversion. The major slip area is distributed in the crust-crust contact zone along the plate boundary including the rupture areas of the 1981 Miyagi-oki and 2003 Fukushima-oki earthquakes. The rupture area of the 1978 Miyagi-oki earthquake must also slip coseismically. We can conclude that the huge earthquake in 2011 includes the Miyagi-oki earthquake, which had been expected to occur in several years time.

Acknowledgments. We would like to thank Professor Jeff Freymueller and Dr. Shin'ichi Miyazaki for their thoughtful reviews of the manuscript. We thank the Miyagi Prefectural government for providing us helicopter flights to collect the GPS data from the Kinkasan and Enoshima islands. Some GPS data were provided by a research project conducted by the Japan Nuclear Energy Safety Organization to establish the evaluation techniques of seismogenic faults. We thank the Geospatial Information Authority of Japan for providing GPS data. The figures were drawn using GMT software (Wessel and Smith, 1998).

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