Displacement Above the Hypocenter of the 2011 Tohoku-Oki Earthquake

Mariko Sato,[1]* Tadashi Ishikawa,[1] Naoto Ujihara,[1] Shigeru Yoshida,[1] Masayuki Fujita,[1] Masashi Mochizuki,[2] Akira Asada[2]

On 11 March 2011, a large interplate earthquake [moment magnitude (M_w) = 9.0] occurred at the plate boundary off Miyagi Prefecture, northeastern Japan. The focal region inferred from the distribution of aftershocks stretches about 500 km long and 200 km wide offshore (*1*).

Various studies have been under way to understand the mechanism of occurrence of this earthquake. For example, the Geospatial Information Authority of Japan (GSI) has reported coseismic displacements on land, on the basis of the dense Global Positioning System (GPS) network (*2*). The largest displacement has been detected at the Oshika peninsula (Fig. 1), amounting to about 5 m toward east-southeast (ESE) and about 1 m downward. The GSI also estimated slip distribution on the plate boundary from the observed displacements, and the maximum slip was about 24 m near the hypocenter (*2*). Because the Oshika peninsula is located about 130 km away from the epicenter of the earthquake, it is preferable to measure crustal movements closer to the focal regions, that is, on the sea floor, to better constrain the focal mechanism of the event.

In order to monitor crustal movements offshore, we have been carrying out sea-floor geodetic observations by using the GPS/acoustic combination technique (*3*–*5*) (fig. S1). Five sea-floor reference points were installed off the Tohoku region between 2000 and 2004 (Fig. 1) with campaign observations carried out three times a year on average.

The latest observations before the event were conducted in November 2010 at KAMS and KAMN and in February 2011 at MYGI, MYGW, and FUKU. After the event, we conducted observations at these sites for the period from 28 March to 5 April (*6*).

Comparison between before and after the event yielded coseismic displacements of 5 to 24 m toward ESE and –0.8 to 3 m upward (Fig. 1, table S1). In particular, at MYGI near the epicenter, we detected a huge coseismic displacement of about 24 m toward ESE and about 3 m upward. Observation errors after the event are somewhat large (up to 50 to 60 cm) compared with those in regular campaigns (up to several centimeters) (*6*). The observed displacements include any postseismic movements for about 20 days after the mainshock. They would also include coseismic displacements by foreshocks and aftershocks (*1*), some of which are large enough to affect these sites. However, a displacement caused by each of them is estimated to be a few tens of centimeters at most, and the total amount other than that of the coseismic signal by the mainshock is not larger than 1 m. Therefore, these data illustrate huge coseismic movements and its spatial variance by the mainshock just above the focal region.

The horizontal movement at MYGI is more than four times larger than that detected on land and almost equal to the maximum slip on the plate boundary inferred from terrestrial measurements (*2*). Additionally, the horizontal displacement at KAMS, located about 70 km northeast of the epicenter, is as large as that at MYGI. Therefore, it is reasonable to interpret that the area where coseismic displacement is greater than 20 m spans at least 70 km. These results suggest that slip on the plate boundary near the trench exceeded the 20- to 30-m level estimated as a maximum by the terrestrial data (*2*), because slip on the plate boundary should be much larger than displacement of the sea floor.

It is also evident that the up-down components of displacement at MYGI and MYGW show opposite polarity. Because the terrestrial data exhibit subsidence (*2*), the polar reversal of the vertical displacement from downward to upward expected from the upper plate rebound at the event occurred offshore. Thus, the hinge line corresponding to null displacement is located on the east side of MYGW.

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

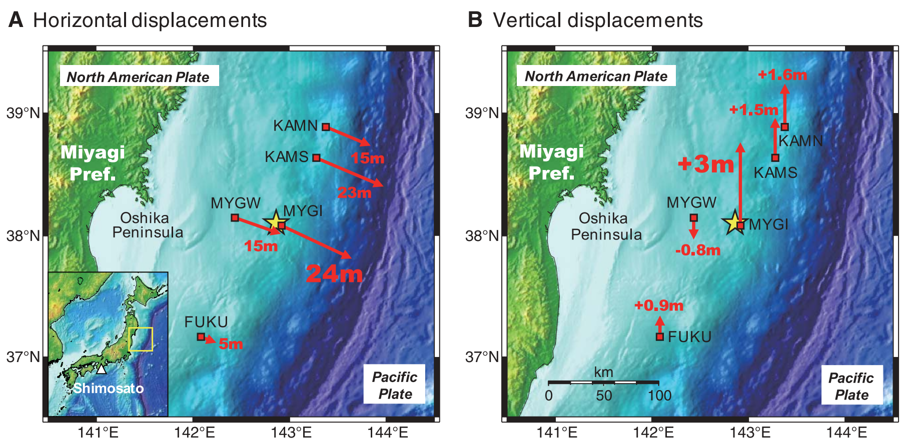

Fig. 1. Horizontal (**A**) and vertical (**B**) coseismic displacements at the sea-floor reference points, associated with the 2011 Tohoku-Oki earthquake. Red squares and a yellow star show locations of sea-floor reference points and the epicenter, respectively. The position reference is Shimosato (an open triangle).

References and Notes

1. Japan Meteorological Agency, www.jma.go.jp/jma/en/2011_Earthquake.html (2011).
2. Geospatial Information Authority of Japan, www.gsi.go.jp/cais/topic110421-index-e.html (2011).
3. A. Asada, T. Yabuki, *Proc. Jpn. Acad. Ser. B* **77**, 7 (2001).
4. M. Fujita *et al.*, *Earth Planets Space* **58**, 265 (2006).
5. M. Sato *et al.*, *Geophys. Res. Lett.* **38**, L01312 (2011).
6. Materials and methods are available as supporting material on *Science* Online.

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Supporting Online Material
www.sciencemag.org/cgi/content/full/science.1207401/DC1
Materials and Methods
Fig. S1
Table S1
References

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[1]Hydrographic and Oceanographic Department, Japan Coast Guard, 5-3-1 Tsukiji, Chuo-ku, Tokyo 104-0045, Japan. [2]Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan.

*To whom correspondence should be addressed. E-mail: eisei@jodc.go.jp

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The Quake That Rocked Japan
The 11 March 2011 magnitude 9.0 Tohoku-Oki megathrust earthquake just off the Eastern coast of Japan was one of the largest earthquakes in recorded history. Japan's considerable investment in seismic and geodetic networks allowed for the collection of rapid and reliable data on the mechanics of the earthquake and the devastating tsunami that followed (see the Perspective by **Heki**). **Sato *et al.*** (p. 1395, published online 19 May) describe the huge displacements from ocean bottom transponders––previously placed directly above the earthquake's hypocenter––communicating with Global Positioning System (GPS) receivers aboard a ship. **Simons *et al.*** (p. 1421, published online 19 May) used land-based GPS receivers and tsunami gauge measurements to model the kinematics and extent of the earthquake, comparing it to past earthquakes in Japan and elsewhere. Finally, **Ide *et al.*** (p. 1426, published online 19 May) used finite-source imaging to model the evolution of the earthquake's rupture that revealed a strong depth dependence in both slip and seismic energy. These initial results provide fundamental insights into the behavior of rare, very large earthquakes that may aid in preparation and early warning efforts for future tsunamis following subduction zone earthquakes.

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