Undersea co-seismic crustal movements associated with the 2005 Off Miyagi Prefecture Earthquake detected by GPS/acoustic seafloor geodetic observation

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We have been carrying out seafloor geodetic observations at two reference points situated off Miyagi Prefecture, northeastern Japan, using the GPS/Acoustic combination technique. Comparison of position estimates before and after the 2005 Off-Miyagi Prefecture Earthquake revealed a co-seismic crustal movement as large as 10 cm eastward at the site approximately 10 km from the epicenter, while no prominent movement was found at another site located 60 km away from the epicenter. The results at these two sites are consistent with crustal deformation calculated from the rectangular dislocation model on the fault derived from crustal movements observed at GEONET stations on land.
Key words: GPS/acoustic, seafloor geodetic observation, co-seismic crustal movement, the 2005 Off Miyagi Prefecture Earthquake.

1. Introduction

Off-shore of Miyagi Prefecture is one of the most seismogenic zones in Japan where a major convergent plate boundary, the Japan Trench, is located. This region has experienced huge interplate earthquakes repeatedly at relatively regular intervals of 30–40 years. Various research projects has been directed towards investigating the interplate coupling of this region with the aim of determining the characteristics of future hazardous earthquakes as well as elucidating the active tectonics of this region. Among these, that of the back-slip estimation based on crustal surface deformation data is one of the major studies to reveal the distribution of asperities in this region (e.g. Nishimura *et al.*, 2000; Suwa *et al.*, 2004).

On 16 August 2005, a large earthquake (M_W=7.2) occurred on the plate boundary off Miyagi Prefecture at a depth of approximately 40 km. This event caused some damage, and a small tsunami was observed on the Pacific coast with a height of at most 0.1 m. The focal mechanism showed a reverse fault with a compression axis in a WNW-ESE direction. GPS observations at the GEONET stations on land detected horizontal movements of approximately 6 cm at most from the southeast to the east extensively in and around Miyagi prefecture and subsidences of approximately 5 cm at most in the Oshika peninsula (GSI, 2005). Although these observations on land produced a fault model that was mostly consistent with the focal mechanism and distribution of aftershocks (JMA, 2005), it is desirable to have data in the offshore region closer to the undersea focal area to better constrain the slip distribution estimation in the rupture area.

Precise seafloor geodetic observation with a GPS/Acoustic combination technique is an emerging methodology to complement missing data on crustal deformation in the sea area, and the original basis for this approach dates back to the early work carried out by scientists at the Scripps Institution of Oceanography (Spiess, 1985). In Japan, our team at the Hydrographic and Oceanographic Department of Japan (JHOD) and the Institute of Industrial Science, the University of Tokyo has been developing this technique using a survey vessel and making repeated campaign observations along the major trenches (Asada and Yabuki, 2001; Mochizuki *et al.*, 2003, 2005; Fujita *et al.*, 2006). Fujita *et al.* (2006) have shown that the repeatability of the position determination reaches a couple of centimeters under good conditions.

In the region off Miyagi Prefecture, we have installed two seafloor reference points on the landward side of the Japan Trench. The primary purpose of our observation in this region is to detect and monitor the secular intraplate crustal movement caused by the subduction of the Pacific plate near the plate boundary. Fujita *et al.* (2006) recently estimated the undersea intraplate crustal velocity at one of our reference points to be more than several centimeters per year towards the WNW. The Tohoku University group has also installed some seafloor stations in this region, and Funakoshi *et al.* (2005) reported that they have detected the intraplate deformation with a similar observation system but using a towed-buoy.

The detection of co-seismic movement is another target of the precise seafloor geodetic observation. Tadokoro *et al.* (2005), in the Nagoya University group, have succeeded in detecting co-seismic crustal deformation at their reference point in the Kumano Basin, near the Nankai trough, associated with the 2004 Offshore Southeast of the Kii Peninsula Earthquakes.

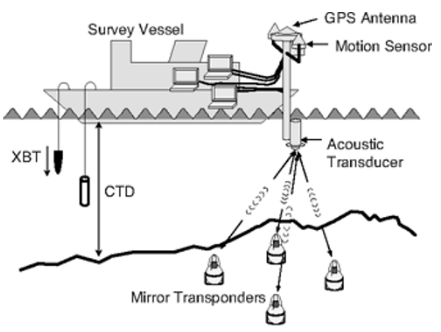

Fig. 1. Schematic picture of the GPS/Acoustic seafloor geodetic observation system.

In this paper, we present and discuss the undersea co-seismic crustal movement associated with the 2005 Off Miyagi Prefecture Earthquake that we have detected at our seafloor reference points during our intensive observations carried out in 2005.

2. Seafloor Geodetic Observation and Analysis

A schematic picture of the seafloor geodetic observation system that we have developed is shown in Fig. 1. This system consists of a seafloor unit with four or three acoustic mirror-type transponders and an on-board unit with a GPS antenna and an undersea transducer installed on the rigid observation pole (8 m in length) to which a dynamic motion sensor is also attached.

The system measures ranges from the on-board transducer to the seafloor acoustic transponders through round-trip acoustic travel times in-between, while simultaneously determining coordinates of the on-board transducer that are transferred from those of the GPS antenna, with the attitude of the observation pole measured with the dynamic motion sensor taken into account. Positions of the GPS antenna are determined using a kinematic GPS software called 'IT' (for Interferometric Translocation), which was developed for the precise determination of the trajectory of a rover over very long baselines (Colombo and Evans, 1998; Colombo *et al.*, 2000, 2001).The acoustic wave velocity profile in the seawater, which is necessary for transforming travel time into range, is obtained from CTD/XCTD and XBT measurements.

Positions of the transponders are finally calculated by a linear inversion method based on least squares formulation combining round-trip travel times and KGPS positions. The positions of grouped transponders are finally averaged to be a virtual position of the reference point.

For more details on the methodology, the reader is referred to Fujita *et al.* (2006)

3. Used Seafloor Reference Points and Intensive Campaign Observations

The locations of the two seafloor reference points and the epicenter of the 2005 Off Miyagi Prefecture Earthquake are shown in Fig. 2.

The site labeled as MYGW is situated about 150 km landward from the axis of the Japan Trench. It is as close as 10 km away from the epicenter of the 2005 Off Miyagi Prefecture Earthquake. A set of three acoustic transponders has been installed on the seafloor, at a depth of about 1100 m. The transponders are placed to form a triangle with an east-west edge and a northerly vertex. In 2005, we carried out four campaign observations at MYGW for the period from June to October.

The second site, labeled as MYGI, is situated about 100 km landward from the axis of the Japan Trench and is 60 km away from the epicenter of the earthquake. It is on the eastern edge of the possible rupture area of the upcoming large interplate earthquake. A set of four acoustic transponders has been installed on the seafloor, at a depth of about 1700 m. The transponders are placed to form a square whose corners are directed to the north, south, east and west. This reference point has been working since 2001. In 2005, we carried out six campaign observations at MYGI for the period from April to October.

4. Results

4.1 The seafloor reference point MYGW

Among the four campaign observations we have carried out, two of them were competed before the 2005 Off Miyagi

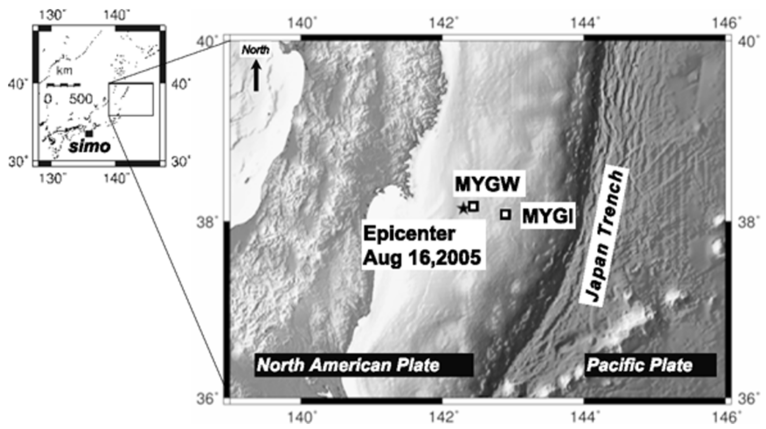

Fig. 2. Locations of the seafloor reference points (open squares) used in this study shown on the topographic map around northeastern Japan. Also shown is the epicenter of the 2005 Off Miyagi Earthquake and the position reference, the Shimosato site (a solid square labeled as 'simo').

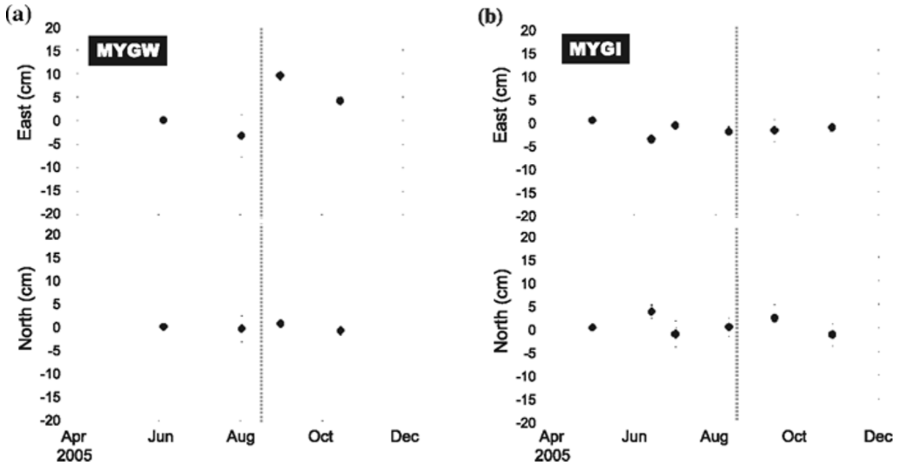

Fig. 3. (a) Time series in the horizontal components obtained at the seafloor reference station MYGW from four campaign observations during the period from June to October, 2005. The top and bottom panels correspond to the EW and NS components, respectively. A vertical broken line represents the occurrence of the 2005 Off Miyagi Prefecture Earthquake. The position reference is the Shimosato site, in central Japan. (b) The same time series for the seafloor reference station MYGI obtained from six campaign observations during the period from April to October, 2005.

Table 1. (a) List of numbers of data for each campaign observation at the seafloor reference point MYGW used in this study. RMS of round-trip travel time residuals for each campaign analysis are also listed. (b) The same list for the seafloor reference point MYGI.

(a)

Epoch	Jun 2005	Aug 2005	Sep 2005	Oct 2005
Days	5	6	5	6
Shots	5817	9091	7015	7011
Residuals RMS (ms)	0.059	0.073	0.053	0.086

(b)

Epoch	**Apr 2005**	**Jun 2005**	**Jul 2005**	**Aug 2005**	**Sep 2005**	**Oct 2005**
Days	**5**	**3**	**4**	**6**	**5**	**6**
Shots	**6465**	**3552**	**5321**	**7408**	**5921**	**6314**
Residuals RMS (ms)	**0.077**	**0.053**	**0.076**	**0.054**	**0.079**	**0.091**

Prefecture Earthquake, and the other two were done afterwards. Data numbers for each campaign epoch used in this paper are listed in Table 1(a). Each epoch consists of five or six observation days. The RMS of round-trip travel time residuals for each campaign analysis, also shown in Table 1(a), are 50–90 s, which corresponds to 4–7 cm in the one-way range.

Figure 3(a) shows the time series of estimated horizontal coordinates. Each solid circle represents the average of the coordinates of three acoustic transponders on the seafloor, relative to the reference campaign epoch of June 2005. Error bars demonstrate changes in the configuration of the three transponders compared to that of the reference solution (see Fujita *et al.* (2006) for more details). The position reference is the Shimosato site, in Wakayama Prefecture, in central Japan, which is one of the ITRF stations also equipped for Satellite Laser Ranging (SLR) observations (Altamimi *et al.*, 2002).

Differences between the average positions of the epochs before and after the earthquake indicates an easterly co-seismic movement of about 10 cm.

4.2 The seafloor reference point MYGI

Among the six campaign observations at MYGI in 2005, four were carried out before the 2005 Off Miyagi Prefecture Earthquake, and two were done afterwards. The strategy of analysis is almost the same as that for MYGW. One minor strategic difference is the application of ‘height constraint’, which is usually very effective for obtaining horizontal coordinates as accurately as possible (Fujita *et al.*, 2006; Ishikawa and Fujita, 2005). We used a height value formerly obtained from the epoch in May 2002 for the constrained height through analyses for all the epochs.

Data numbers for each epoch used in this paper are listed in Table 1(b). Most of the epochs have more than four observation days. Round-trip travel time residuals for each campaign analysis, also shown in Table 1(b), are at the same level as that of MYGW.

Figure 3(b) shows the time series of estimated horizontal coordinates relative to the reference campaign epoch of April 2005.

The positions obtained for two epochs after the 2005 Off Miyagi Prefecture Earthquake appear to be within an error range—several centimeters—compared with those before the event.

5. Discussion

Based on onshore geodetic and geophysical observations, several research groups have estimated slip distribution of the earthquake (e.g. Sekiguchi *et al.*, 2005; Tanioka *et al.*, 2005). We have compared our results with a rectangular fault model proposed by GSI (2005) using GEONET GPS data. The estimated vector of the movement of the seafloor reference point MYGW from our observation is shown in Fig. 4, with superposed synthetic vectors of crustal deformation predicted by this model at MYGW and MYGI. The movement at MYGW is highly consistent with the synthetic vector in both magnitude and direction.

On the other hand, no prominent movement was de-

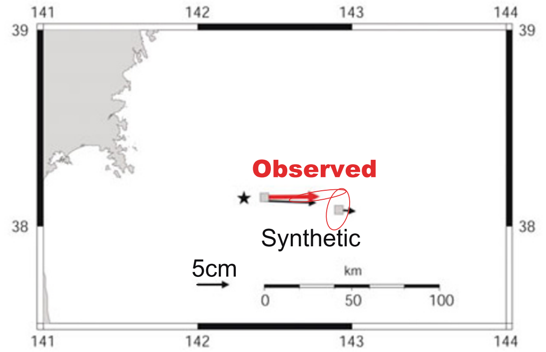

Fig. 4. Undersea coseismic horizontal crustal movements associated with the 2005 Off Miyagi Prefecture Earthquake. The movement of the reference station MYGW obtained from our seafloor geodetic observation is shown by the thick red arrow. The movement of MYGI is substantially zero. 1σ Error ellipses are shown for both of them. Synthetic vectors of the crustal deformation at two reference points under GSI's rectangular fault model are also shown by thin black arrows.

tected at MYGI based on our observations, while the GSI model predicts an easterly movement of 2.6 cm. In view of the precision of our observations—accurate to several centimeters—this result is regarded to be still consistent with the model rather than inconsistent, since such a scale of movement is below the detectable level of our observations.

Based on these results, we conclude, at this stage, that the observed undersea crustal movements close to the focal area support the overall picture on the rupture area derived from the remote GPS observations on land.

6. Summary

We have carried out precise seafloor geodetic observations with the GPS/Acoustic combination technique at two seafloor reference points near the epicenter of the 2005 Off Miyagi Prefecture Earthquake. Intensive campaign observations in 2005 in this region detected an easterly coseismic movement of about 10 cm at the seafloor reference point MYGW, 10 km away from the epicenter, while no prominent movement was found at the other site MYGI, 60 km away from the epicenter. These results are consistent with synthetic displacement vectors calculated from the GSI's rectangular fault model of this earthquake: they are quite consistent at MYGW and below the detectable level at MYGI.

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