Obana *et al. Earth, Planets and Space* 2014, **66**:24
http://www.earth-planets-space.com/content/66/1/24

Earth, Planets and Space
a SpringerOpen Journal

FULL PAPER Open Access

Aftershocks of the December 7, 2012 intraplate doublet near the Japan Trench axis

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Abstract

On December 7, 2012, a pair of large Mw 7.2 intraplate earthquakes occurred near the Japan Trench axis off Miyagi, northeast Japan. This doublet consisted of a deep reverse-faulting event followed by a shallow normal-faulting event. Aftershock observations using conventional and newly developed ultra-deep ocean bottom seismographs in the trench axis area showed that the shallow normal-faulting event occurred in the subducting Pacific plate just landward of the trench axis. The shallow normal-faulting aftershock activity indicated that in-plate tension in the incoming/subducting Pacific plate extends to a depth of at least 30 km, which is deeper than before the 2011 Tohoku-Oki earthquake, whereas in-plate compression occurs at depths of more than 50 km. Hence, we concluded that the neutral plane of the in-plate stress is located between depths of 30 and 50 km near the trench axis.

Keywords: Japan Trench; Intraplate doublet; Stress state; Subduction zone; 2011 Tohoku-Oki earthquake

Background

On December 7, 2012, a pair of large intraplate earthquakes occurred at the Japan Trench off Miyagi, northeast Japan (Figure 1). According to the Global CMT Project (GCMT, http://www.globalcmt.org/), a Mw 7.2 deep reverse-faulting earthquake was followed by another Mw 7.2 shallow normal-faulting earthquake about 12 s later. The centroid depths of these events were 57.8 and 19.5 km. This intraplate doublet generated a tsunami, which was observed along the Pacific coast of northeast Japan with a maximum height of about 1 m (Japan Meteorological Agency 2012).

This doublet occurred seaward of the largest coseismic slip area during the 2011 Mw 9.0 Tohoku-Oki earthquake. The 2011 Tohoku-Oki earthquake ruptured the subduction megathrust with a maximum slip of about 50 m (e.g., Yagi and Fukahata 2011). Since the 2011 Mw 9.0 Tohoku-Oki earthquake, shallow normal-faulting seismicity has been active in the incoming/subducting Pacific plate near the Japan Trench (e.g., Asano et al. 2011). This normal-faulting earthquake activity was enhanced by the increased tensional stresses caused by the large coseismic slip along the plate interface (Lay et al. 2011). Recent studies on the relation between subduction megathrust and intraplate earthquakes, which include shallow normal and deep reverse-faulting intraplate events, have shown spatial and temporal interactions among them (Lay et al. 2013; Todd and Lay 2013). However, these studies were based on teleseismic analysis with limited accuracy in terms of the location, especially the depth. Accurately determining the locations of earthquakes is essential for quantitative understanding of the stress state near the trench axis.

We analyzed the ocean bottom seismograph (OBS) data to accurately obtain the location and focal mechanisms for the aftershocks of the December 7, 2012 Japan Trench doublet and to understand the stress regime within the incoming/subducting Pacific plate near the axis of the Japan Trench. Stresses within the Pacific plate near the Japan trench are characterized by shallow tension and deep compression caused by plate bending (Gamage et al. 2009; Hino et al. 2009). OBS observations after the 2011 Tohoku-Oki earthquake showed that the 2011 earthquake changed the stress regime in the Pacific plate and that the tensional stress, which was previously limited to depths shallower than 20 km, now extends to depths of about 40 km (Obana et al. 2012). However, no compressional earthquakes had been observed in the Pacific

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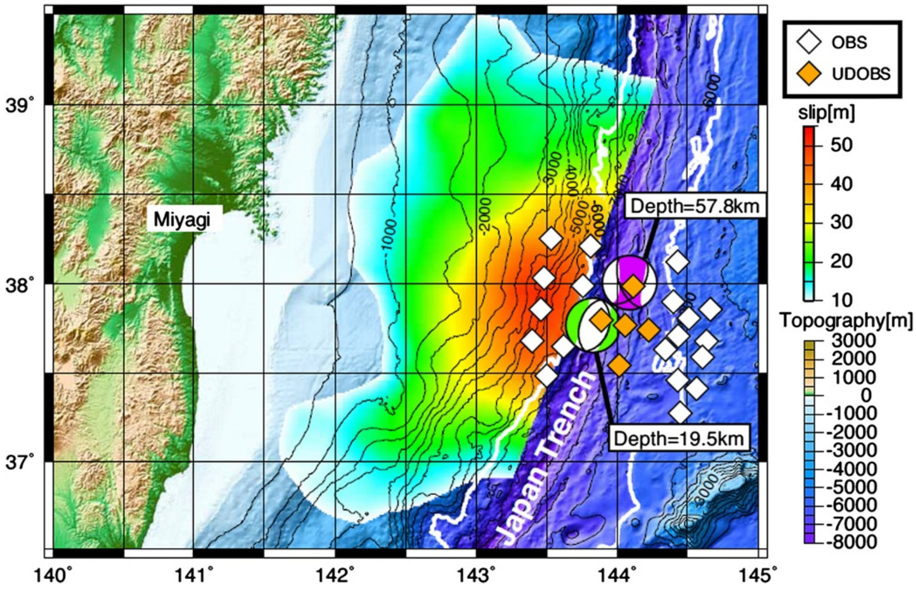

Figure 1 Map of the study area. Bathymetric map showing the locations of conventional ocean bottom seismographs (OBS) and ultra-deep ocean bottom seismographs (UDOBS) used in this study and centroid moment tensor solutions of December 7, 2012 intraplate doublet earthquakes by the Global CMT Projects. The iso-depth contour of the 6,000-m water depth is indicated by the thick white line. The total slip distribution of larger than 10 m of the 2011 Tohoku-Oki earthquake from Yagi and Fukahata (2011) is also shown.

plate during OBS observations after the 2011 earthquake. Hence, the stresses in the deeper part of the Pacific plate were unclear. The pair of deep reverse-faulting and shallow normal-faulting earthquakes provided an opportunity to evaluate the depth dependency of the stress state in the Pacific plate near the trench.

Methods

Observations and analysis

Our ocean bottom seismograph (OBS) observations began on December 13, 2012. We deployed 26 OBSs from the R/V *Kairei* of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Figure 1). The Japan Trench doublet on December 7, 2012 occurred close to the trench axis with a maximum water depth of about 8,000 m. Conventional OBSs are usually limited to depths shallower than 6,000 m; thus, they could not be used at the trench axis (e.g., Obana et al. 2012). We used the newly developed ultra-deep OBSs (UDOBSs) in this study (Maeda et al. 2013). A UDOBS is equipped with a spherical ceramic pressure housing and can be deployed at depths of up to 9,000 m. The dimensions and weight of a UDOBS are comparable to those of a conventional OBS; hence, we could handle the UDOBSs in the same way as conventional OBSs. We deployed five UDOBSs near the trench axis at a water depth of more than 6,000 m and 21 conventional OBSs on both the inner and outer trench-slope areas. All UDOBSs and OBSs were equipped with a three-component 4.5-Hz short-period seismometer. Seismic signals were recorded continuously at a sampling frequency of 100 Hz with a 16-bit analog-to-digital converter. All OBSs were recovered by January 6, 2013 except for two conventional OBSs, which we were unable to recover. Hence, we used 24 OBSs, as shown in Figure 1.

We manually picked P- and S-wave arrival times for earthquakes listed in the preliminary earthquake catalog by the Japan Meteorological Agency (JMA). We selected about 400 earthquakes within the catalog that were located between 37°N and 39°N and east of 143°E. Where possible, we used the polarity of P-wave first motions to estimate focal mechanisms.

We calculated hypocenter locations and focal mechanisms using a 2-D seismic velocity model with a grid-search technique. The velocity model was derived using a first-arrival tomography method based on active seismic survey data along line MY102 across the observation area Ito et al. (2005) (Figure 2). The east end of the 2-D velocity model by Ito et al. (2005) was about 25 km east of the trench axis. We assumed that the velocity profile further east was the same as that at the eastern edge of their 2-D velocity model. We also extended the velocity model to a depth of 80 km by using a uniform velocity below 60 km, which was the lowest depth of Ito et al. (2005)'s model.

We searched for hypocenter locations in a 150 km × 150 km region and from the seafloor to a depth of 80 km below sea surface using the same method we described

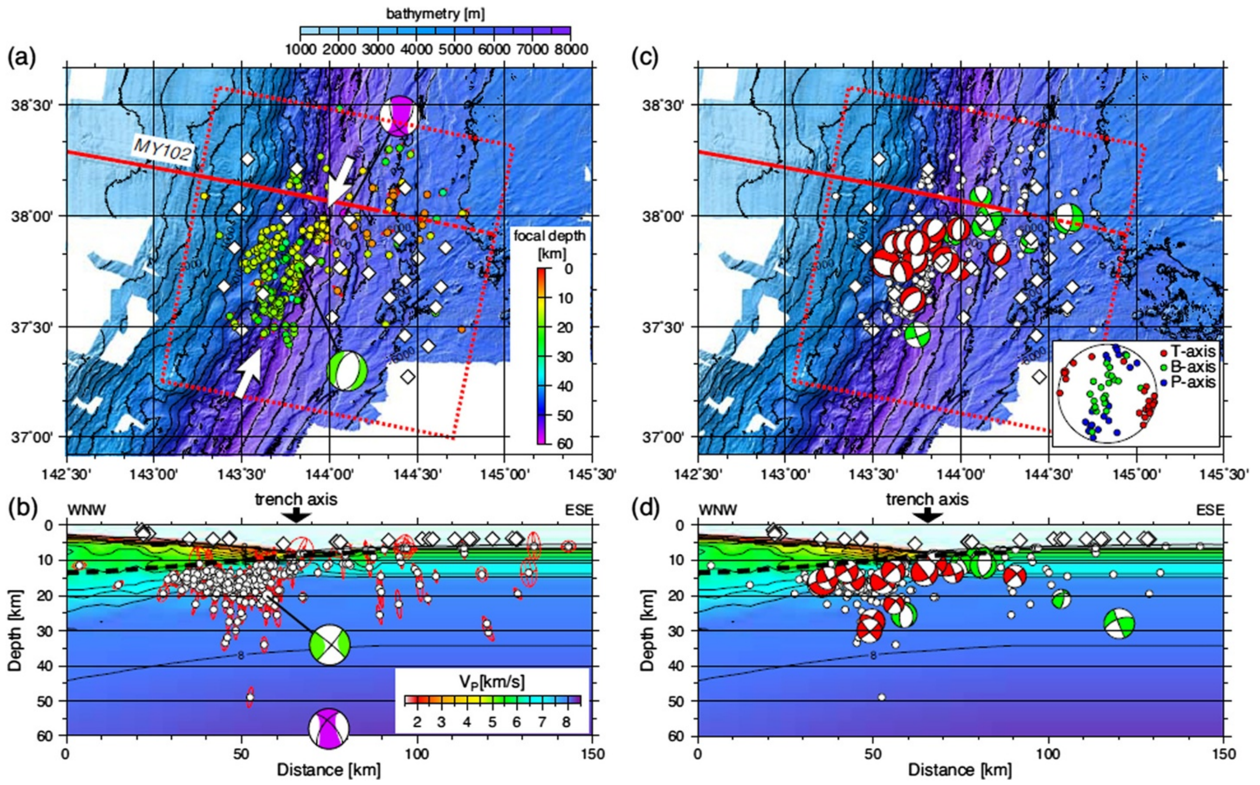

Figure 2 Hypocenter locations and focal mechanisms obtained from the OBS observations. (a) Map showing hypocenter locations and error ellipsoids obtained from the OBS observations. The hypocenters are color-coded by the depth. The OBS locations (diamonds) and centroid moment tensor solutions of December 7, 2012 intraplate doublet earthquakes by the Global CMT Projects (GCMT) are also shown. The arrow indicates the epicentral lineation coinciding with the GCMT solution of the shallow normal-faulting earthquake. The red solid line is the MY102 seismic survey line (Ito et al. 2005). The dashed line on the extension of MY102 indicates the area where the velocity structure was not obtained by the seismic survey. The dotted rectangle indicates the grid-search area for the hypocenter locations. **(b)** Hypocenters and error ellipsoids of earthquakes within the dotted rectangle in **(a)** were projected on the P-wave velocity model along MY102. The dashed line is the top of the subducting oceanic crust (Ito et al. 2005). **(c)** Focal mechanisms obtained from the OBS observations. The red and green focal mechanisms correspond to normal and strike-slip faulting earthquakes grouped by rake angles, respectively. No reverse-faulting focal mechanisms were obtained. The P, B, and T axes of the earthquakes are indicated in the inset. **(d)** Focal mechanisms projected on the cross section along MY102.

previously (Obana et al. 2013) (Figure 2). We calculated the travel times between each OBS and each 0.5-km uniformly spaced grid point in the 3-D search space using the program FAST (Zelt and Barton 1998). We then searched for the optimal location of the hypocenter on a 0.5-km spaced grid based on the minimum travel time residual. We only used the P-wave arrival time data because S-wave velocity structures had not been obtained by previous active seismic surveys in this area (Ito et al. 2005; Miura et al. 2005). We ran the grid search procedure twice. We used the averaged travel time residuals for each OBS ranging between −0.24 and 0.21 s, for the first grid search as station corrections for the second grid search. Thus, the averaged travel time residuals decreased to between −0.05 and 0.05 s for the second search. We also determined magnitudes from the maximum amplitudes of the seismograms (Watanabe 1971).

We located 286 events from December 13, 2012 to January 5, 2013 that each had at least five P-wave arrival time data points and location errors of less than 5 km, which were estimated from the travel time residual distributions in the search space (Figure 2). The magnitudes of these earthquakes ranged from 2.1 to 4.6 and tended to be larger than the magnitudes reported by the JMA (Mj). The magnitude differences relative to Mj ranged from −0.6 to 1.0, and the average difference was 0.45. Most of the earthquakes were located west of the trench axis at depths of shallower than 35 km (Figure 2b). The deepest earthquake was located at a depth of 49 km. There were no earthquakes located in the overriding plate near the trench axis.

We also estimated focal mechanisms from the polarity of the P-wave first motions by using the code HASH (Hardebeck and Shearer 2002). We obtained focal mechanisms for 21 events (M 2.7 to 4.3) with fault plane uncertainties of less than 35° (Figure 2c,d). Most of the focal mechanisms showed normal-faulting, and the others showed strike-slip faulting. The predominant T-axis direction was NW-SE, which is normal to the trench axis. No reverse-faulting focal mechanisms were obtained in this study.

Results and discussion

The earthquakes located in this study mainly occurred beneath the trench inner-slope area and showed a NNE-SSW striking 50-km-long epicentral lineation just west (landward) of the trench axis (Figure 2a). The length of this lineation was consistent with a finite fault slip model of the shallow normal-faulting earthquake of the 2012 Japan Trench doublet obtained from a teleseismic body wave inversion (Harada et al. 2013). This epicentral lineation coinciding with the GCMT solution of the shallow normal-faulting event may indicate the location of the shallow normal-faulting rupture. Strikes of this lineation and nodal planes of the GCMT solution were almost parallel. Focal mechanisms of the earthquakes west of the Japan Trench indicated normal-faulting similar to the GCMT solution (Figure 2). Although Lay et al. (2013) estimated the location of the shallow normal-faulting event to be east of the Japan Trench based on a two double-couple W-phase inversion, the GCMT solution was located within the uncertainty of the W-phase inversion. Hence, we believe that the shallow normal-faulting event of the 2012 Japan Trench doublet occurred just west (landward) of the trench axis.

On the other hand, the location of the deeper reverse-faulting event in the December 7, 2012 doublet is unclear. All of the earthquakes we observed with OBSs were located at depths of shallower than 35 km except for one at a depth of about 50 km (Figure 2b). Furthermore, no reverse-faulting focal mechanisms were obtained from the OBS observations (Figure 2c,d). Both the GCMT and Lay et al. (2013) showed that the relative location of the deep reverse-faulting event was about 30 km NNE from the shallow normal-faulting event. Considering the agreement between the GCMT solution of the shallow normal-faulting event and the epicentral lineations of the earthquakes just west of the trench axis derived from the OBS observations, the deep reverse-faulting event of the 2012 Japan Trench doublet may have also occurred near the GCMT solution for this event. The deepest event in our OBS observations was located at 37°38.7′N and 143°44.5′E about 50 km SSW of the GCMT solution for the deep reverse-faulting event of the December 2012 doublet. The finite fault model of the deep reverse-faulting event showed the rupture extending about 30 km along the strike (Lay et al. 2013). The deepest event from the OBS observations was too far away to be used to argue for the location of the deep reverse-faulting earthquake. However, the deepest event of our OBS observations indicated the potential for earthquakes occurring at depths corresponding to the deep reverse-faulting event obtained by teleseismic analysis.

The shallow normal-faulting aftershocks mainly occurred within 30 km west of the trench axis (Figure 2d). Compared with the time-migrated sections of multichannel reflection surveys (Nakamura et al., 2011; 2013), the shallow earthquakes landward of the trench axis mainly occurred in the oceanic crust (Figure 3). Some of the events were located very close to the top of the oceanic crust, such as along line JFD1 near the IODP JFAST drilling site (Chester et al. 2012). These earthquakes showed several clusters or lineations, and some coincided with normal faults cutting the oceanic crust and forming horst and graben structures (Figure 3). The oceanic crust of the Pacific plate subducted beneath northeast Japan from the Japan Trench is characterized by horst and graben structures formed by widely distributed normal faults cutting the oceanic crust owing to plate bending (e.g., Nakanishi 2011). The normal faults develop approximately 110 km seaward of the trench and continue to increase their throws until at least 30 km landward from the trench axis based on a reflection survey across the Japan Trench (Tsuru et al. 2000). Seaward of the trench axis, shallow earthquakes within the oceanic crust mainly occurred within 110 km from the trench axis (Obana et al. 2012). The shallow earthquakes within the oceanic crust landward of the trench axis may indicate continued development of normal faults forming horst and graben structures even after subduction.

The focal mechanisms obtained from our OBS observations showed that trench-normal tensional stresses within the subducting Pacific plate extend to a depth of at least about 30 km or even 35 km below the sea surface, which corresponds to 25 km below the top of the oceanic crust, considering the depth range of the active seismicity (Figure 2c,d). The normal-faulting earthquakes occurred at depths of about 40 km in May and June 2011 after the 2011 Tohoku-Oki earthquake (Obana et al. 2012). In contrast, normal-faulting earthquakes were limited to depths of shallower than 20 km before the 2011 Tohoku-Oki earthquake (Hino et al. 2009). The tensional stresses in the Pacific plate still extend deeper than before the 2011 Tohoku-Oki earthquake, although the change in the maximum depth of the normal-faulting earthquakes may indicate a change of the stresses with time after the 2011 earthquake. Thus, large shallow normal-faulting earthquakes can potentially occur within the incoming/subducting Pacific plate along the Japan Trench similar to the 1933 Sanriku earthquake (Lay et al. 2011). On the other hand, the finite-fault model for the deep

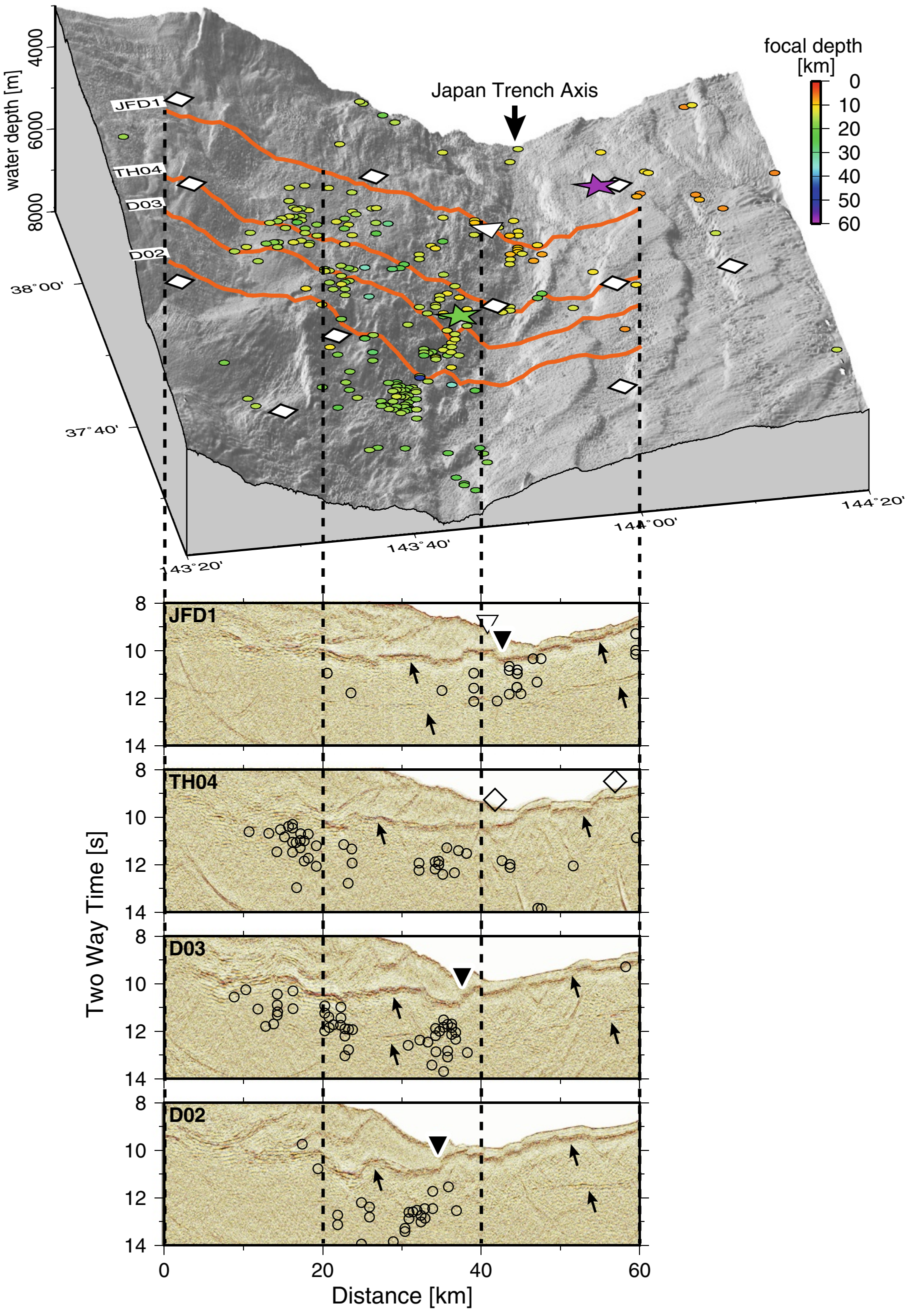

Figure 3 Earthquake locations projected on the perspective view of the bathymetry and time-migrated sections. Hypocenter locations were projected on time-migrated section along four multi-channel reflection survey lines (Nakamura et al., 2011; 2013). Focal depths were converted to two-way times by using the 2-D velocity structure for the hypocenter determination. Stars and circles on the top perspective view indicate centroid locations of the December 7, 2012 Japan Trench doublet by GCMT and hypocenter locations of the earthquakes obtained from the OBS observations, respectively. Colors are coded by hypocentral depth. Earthquakes within 5 km from each survey line are projected on the time-migrated sections. Arrows on the cross sections indicate the top of the subducting oceanic crust and the oceanic Moho. Solid inverted triangles on the cross sections indicate normal faults associated with horst and graben structure and coinciding with the shallow earthquakes. The locations of the OBSs (diamonds) and JFAST drilling site (inverted triangle) (Chester et al. 2012) are also shown.

reverse-faulting event showed that slip was concentrated at depths between 50 and 60 km, which includes the depth of the deepest earthquake observed by our OBS observations (Lay et al. 2013). The stresses in the Pacific plate are likely compressional at depths of more than 50 km.

Conclusions

Our OBS observations indicated that the shallow normal-faulting event of the December 7, 2012 Japan Trench doublet likely occurred in the subducting Pacific plate just west (landward) of the Japan Trench axis. The shallow aftershock activity showed trench-normal tension in the Pacific plate and may indicate normal faults forming the horst and graben structures. The trench-normal tensional stresses extended to a depth of at least 30 km in the incoming/subducting Pacific plate below the sea surface, whereas compression prevailed at depths more than 50 km. This suggests that the neutral plane of the in-plate stresses is located at depths between 30 and 50 km near the trench axis.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

KO, SK, and GF designed the OBS observations. KO analyzed OBS data and wrote the paper. YN contributed to the interpretations of the multi-channel seismic reflection data. TS, TT, and YY participated in data acquisition and processing. All authors read and approved the final manuscript.

Acknowledgements

We thank Thorne Lay and an anonymous reviewer for their helpful comments. This study was supported by the Special Coordination Funds for the Promotion of Science and Technology (MEXT, Japan) titled as integrated research for the 2011 off the Pacific coast of Tohoku Earthquake. Geological Survey of Canada supported KO as a visiting scientist. We thank Roy Hyndman, Garry Rogers, and Kelin Wang for their comments and discussions.

Received: 10 September 2013 Accepted: 25 November 2013
Published: 30 April 2014

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doi:10.1186/1880-5981-66-24
Cite this article as: Obana *et al.*: **Aftershocks of the December 7, 2012 intraplate doublet near the Japan Trench axis.** *Earth, Planets and Space* 2014 **66**:24.