Potential tsunamigenic faults of the 2011 off the Pacific coast of Tohoku Earthquake

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Faults related to the tsunamigenic 2011 Tohoku-Oki Earthquake (M_w 9.0) were investigated by using multi-channel seismic reflection data acquired in 1999 and submersible seafloor observations from 2008. The location of the fault system interpreted in the seismic reflection profile is distributed around the area with largest slip and tsunami induction of the 2011 event. Cold-seep communities along the trace of the branch reverse fault and a high scarp associated with the trace of a normal fault suggest current activity on these faults. We interpret the fault system in the seismic profile as a shallow extension of the seismogenic fault that may have contributed to the resulting huge tsunami.
Key words: 2011 Tohoku-Oki Earthquake, tsunamigenic faults, seismic reflection data, seafloor observation, cold-seep communities, high scarp.

1. Introduction

The 11 March 2011 earthquake (M_w 9.0) ruptured a wide area along the plate interface off the Pacific coast of Tohoku, Japan (Japan Meteorological Agency JMA, 2011; Yagi, 2011; Fig. 1(a)). The northwestern margin of the Pacific plate is subducting beneath the northeastern Japan Arc at a convergence rate of 8.6 cm/yr (DeMets *et al.*, 1990) and frequently generates interplate earthquakes and tsunamis (e.g., Yamanaka and Kikuchi, 2004). However, the tsunami caused by this earthquake was extremely huge, and observations with an ocean bottom pressure gauge revealed short-period spike-shaped sea surface uplift (e.g., Fujii *et al.*, 2011). In order to reveal mechanisms of the impulsive tsunami generation, shallow fault distributions and geometries are important.

Here, we identify a series of faults from a seismic reflection profile obtained in 1999 near the hypocenter (JMA, 2011) and seafloor observations of the fault trace made in 2008 by the manned submersible *Shinkai 6500*. Because the surveyed area includes the region where the largest vertical displacement is predicted to have occurred (Ueno and Satake, 2011; Shao *et al.*, 2011; Fig. 1(a)), the shallow faults here are likely to be directly related to the tsunami characteristics.

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2. Seismic Reflection Data

Multi-channel seismic reflection data acquired by *R/V Kairei* (JAMSTEC) in 1999 (Line MY102 of KR99-08 cruise; Tsuru *et al.*, 2002) were analyzed for an investigation of fault geometry and to select dive points for seafloor observations (Fig. 1(b)). In the seismic survey, the sound source was an array of ∼200-L (12,000 cubic inch) airguns fired every 50 m. The receiver array was a 156-channel, 4-km streamer, and the record length was 13.5 s.

We applied conventional seismic processing, including trace editing, multiple suppression, deconvolution, velocity analysis, stacking, and post-stack migration (Yilmaz, 2001). We then obtained the depth-domain profile (Fig. 2) by using stacking velocity. Due to the limitation of the streamer length, it was difficult to determine seismic velocities accurately in the deeper lithology.

3. Geological Interpretation

On the reflection profile (Fig. 2), we identified three predominant faults branching from the plate boundary fault: (A) a backstop reverse fault acting as a boundary between a seaward accreted sequence and a landward less-deformed Cretaceous sequence (von Huene *et al.*, 1994; Tsuru *et al.*, 2002), (B) a branch reverse fault constructing the significant seafloor slope break (Fig. 2(d)), and (C) a steeply dipping normal fault branching from a plate boundary fault and extending towards a seafloor ridge (Fig. 2(c)). However, potential underplating structures are observed landward of the backstop reverse fault defined by Tsuru *et al.* (2002) (Fig. 2(b)).

Displacement along the steeply-dipping normal fault has

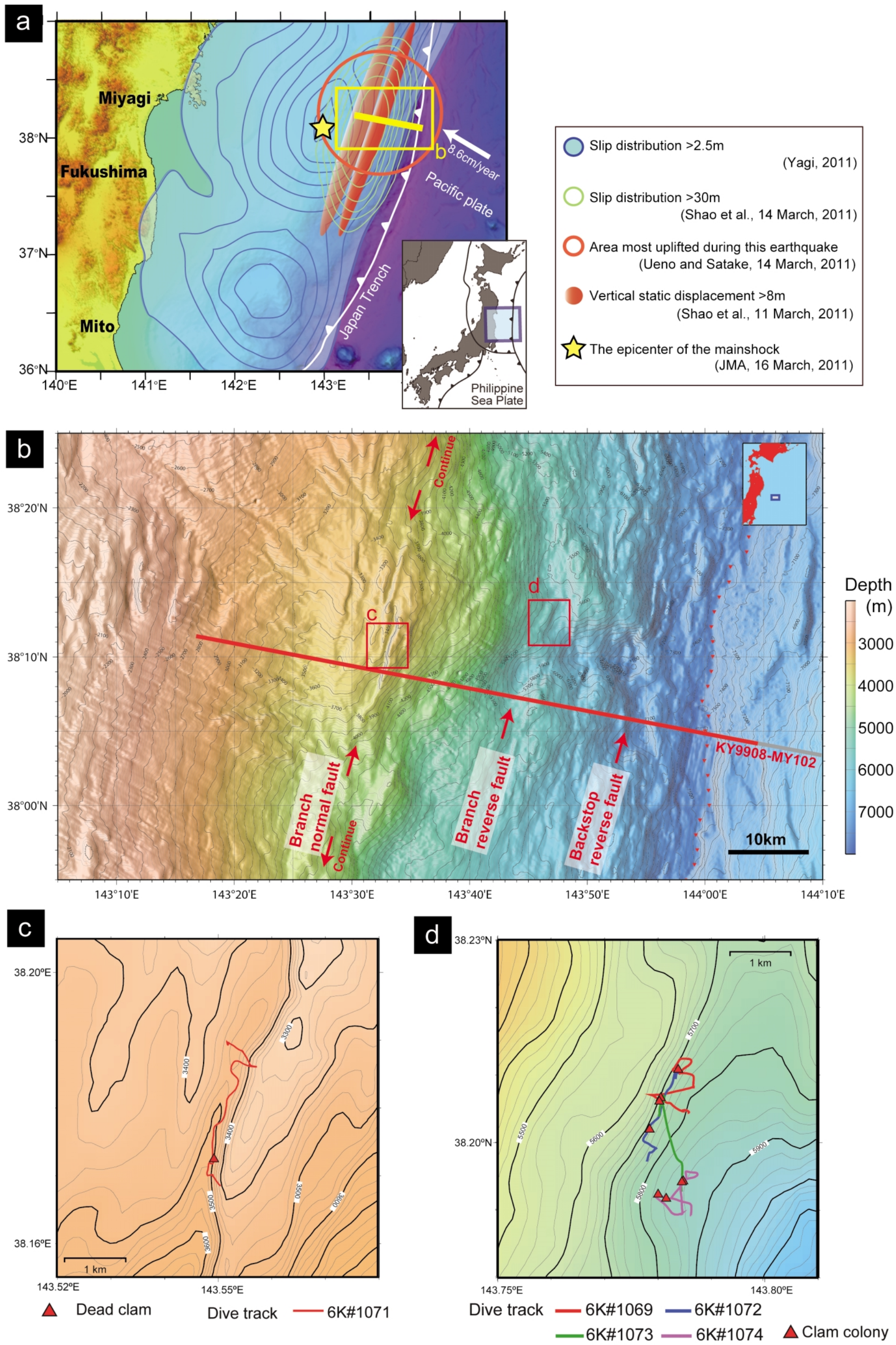

Fig. 1. (a) Seismic survey line (yellow line), energy and slip distribution of the 2011 earthquake, and area of tsunami induction. Yellow rectangle indicates the area of panel (b). (b) Bathymetric map around the seismic survey line (red line) (Sasaki, 2004). Reverse triangles indicate the location of a landward margin of the trench. We identify the ridge associated with steeply dipping normal fault and the seafloor slope break associated with branch reverse faults. Red rectangles indicate the areas of panels (c) and (d). (c) Dive track at the seafloor ridge (Dive #1071). Red triangle indicates the location where a dead clam was observed. (d) Dive tracks at the seafloor trace of the branch reverse fault (Dive #1069, #1072, #1073, and #1074). Red triangles indicate the locations of clam colonies.

offset a Cretaceous sequence surface by ~800 m (Fig. 2(c)). The plate boundary fault and steep normal fault appear to bound a pop-up structure. The seafloor ridge associated with the normal fault displacement is well identified on the seafloor topography (Fig. 1(b)) and is as long as several tens of kilometres parallel to the trench axis. Therefore, the normal fault should play an important role in the plate convergent margin off Miyagi.

4. Submersible Seafloor Observations

In May 2008, we used the manned submersible *Shinkai 6500* (YK08-06) to visit two points along this seismic line: the seafloor trace of the (B) branch reverse fault (Fig. 2(d)) and a ridge associated with displacement along the (C)

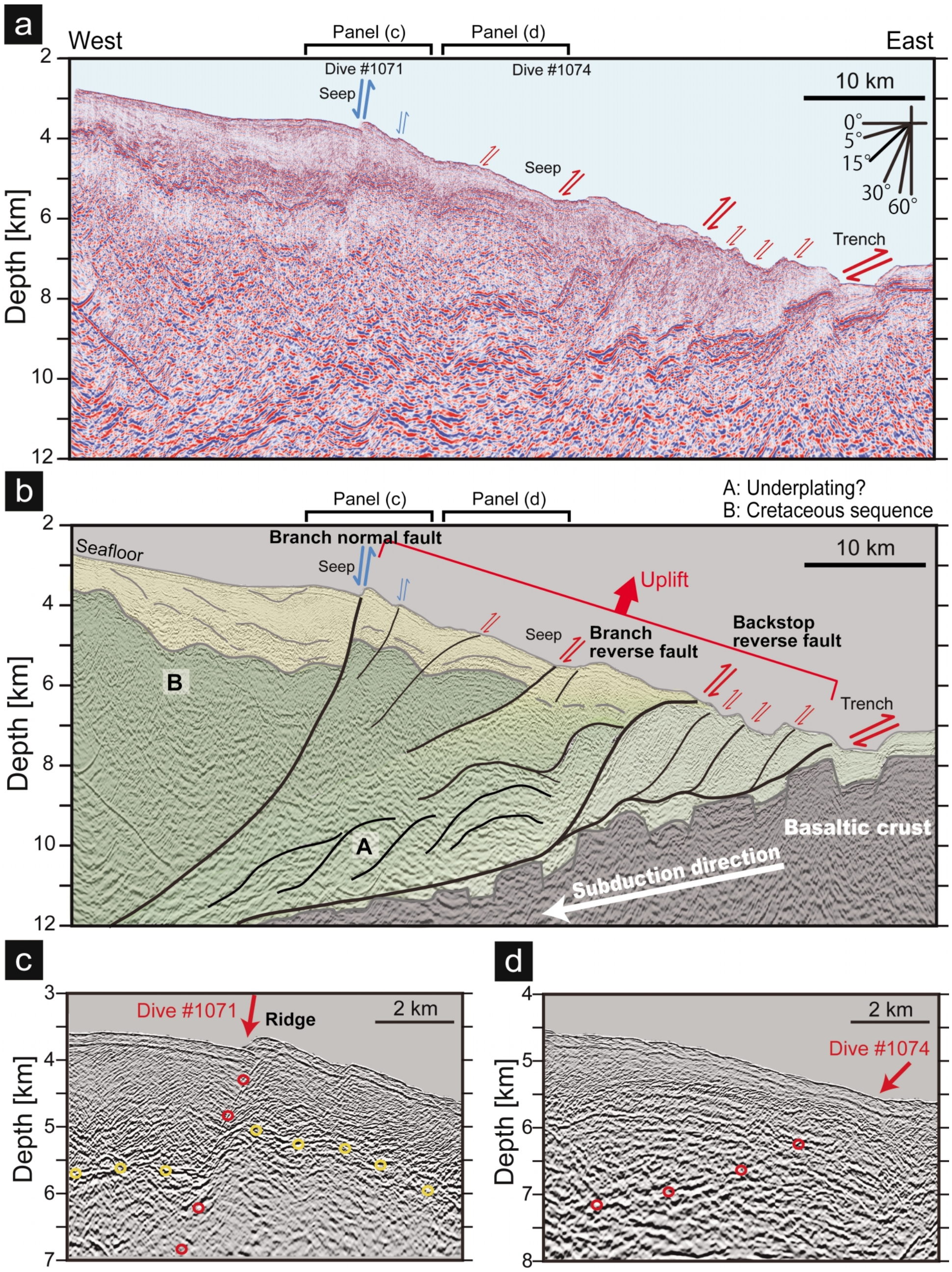

Fig. 2. (a) Original seismic reflection profile with amplitude gain control (AGC). (b) Composite seismic reflection profile with geological interpretations. (c) Detailed profile around the normal fault and ridge structure. Displacement of steeply dipping fault (red dots) offsets the sediment basement surface (yellow dots). (d) Detailed profile around the seafloor trace of branch reverse fault (red dots). The fault can be identified as a clear reflection.

branch normal fault (Fig. 2(c)). Because of an insufficient depth capability of *Shinkai 6500*, we could not dive to the seafloor trace of the (A) backstop reverse fault located at a depth of ~7000 m as well as plate boundary fault (~7500 m).

Chemosynthetic communities observed along the branch reverse fault trace (Figs. 1(d), 2(d), 3(a)) indicate that fluid passes through open fractures along the fault plane. Similar cold seeps on the seafloor traces of active faults in the northern Japan Trench (Ogawa *et al*., 1996) and other convergent margins (Toki *et al*., 2004) suggest that the interpreted faults on the off-Tohoku seismic profile are also active.

A scarp ~150 m high marks the trace of the normal fault (Figs. 1(c), 2(c), 3(b)), and continuously exists along the ridge (~2 km dive track of the *Shinkai*). The slope angle of the scarp is nearly vertical and overhanging in places (Fig. 3(b)). We sampled rocks from the steep scarp and estimated the depositional age as 0.51–0.85 Ma from both calcareous nannofossils (e.g., Okada and Bukry, 1980) and fossil diatoms (e.g., Yanagisawa and Akiba, 1998). Because there is a fresh scarp surface without any manganese coating and because we observed a dead clam there, this scarp may have been generated by recent earthquake activity.

5. Summary and Discussions

Faults related to the tsunamigenic 2011 Tohoku Earthquake were investigated by using seismic reflection data and submersible seafloor observations. The fault system identi-

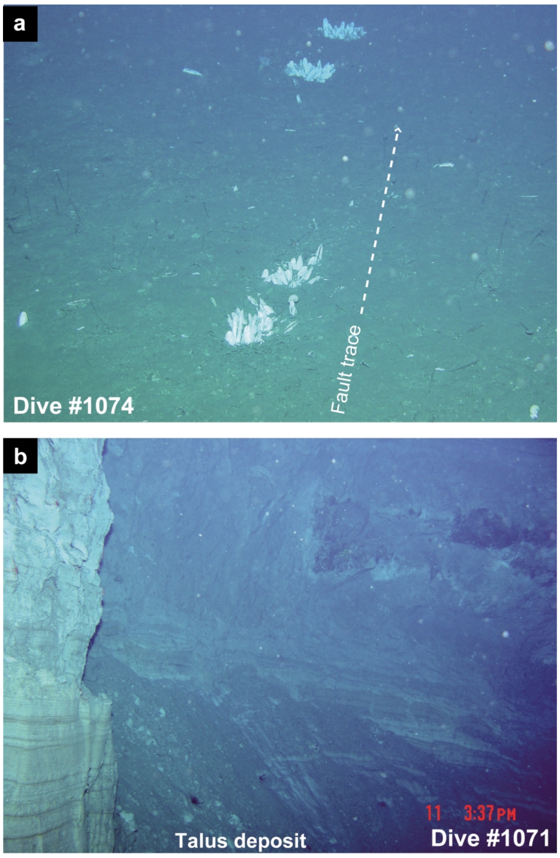

Fig. 3. (a) Chemosynthetic biological communities observed along the seafloor trace of the branch reverse fault (Fig. 2(d)). (b) Still video image (view from north) of the scarp attributed to the displacement of a steeply dipping normal fault (Fig. 2(c)). A fresh surface without manganese coating suggests recent activity of the normal fault.

fied in this study is located at the seaward edge of the rupture area (Yagi, 2011) or consistent with the maximum rupture area (JMA, 2011; Shao *et al*., 2011) (Fig. 1(a)). The largest tsunami was inferred to have been induced near the interpreted fault (Ueno and Satake, 2011) where the largest vertical static displacement is expected (Shao *et al*., 2011). Therefore, the interpreted fault system may be shallow extensions of the seismogenic fault that also slipped during the earthquake.

Seafloor displacement during the earthquake estimated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC, 2011) demonstrated that the seafloor between the trench and the normal fault is significantly deformed in a seaward direction (50 m horizontal displacement) and uplifted (7 m vertical displacement). Therefore, the normal fault seems to act as a landward boundary of a significant displacement region. This observation suggests that the geological unit between the normal fault and the plate boundary fault should be uplifted (moves to seaward direction), as inferred from the fault interpretations on seismic profile (Fig. 2(b)).

Because displacement along the plate boundary fault near the trench is much larger than the deeper fault landward of our survey area (e.g., Fujii *et al*., 2011), the geological unit above the plate boundary fault is in a tensile state of stress. Due to the tensile stress state, the normal faults should be ruptured during this earthquake event.

If the steeply-dipping normal faults slipped during the earthquake, in addition to the plate boundary fault, they can induce the huge tsunami even as a result of a smaller displacement. The potential underplating unit landward of the backstop reverse fault may also have caused uplift that contributed to the tsunami.

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