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SEISMOGENIC FAULTS OF THE 2011 GREAT EAST JAPAN EARTHQUAKE: INSIGHT FROM SEISMIC DATA AND SEAFLOOR OBSERVATIONS

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ABSTRACT:

Faults related to the 2011 Tohoku earthquake were investigated using seismic data and submersible seafloor observations conducted before and after the earthquake. Seismic profiles image several normal faults within continental crust. The seafloor observations after the earthquake demonstrate that open fissures are developed along the fault traces which could not be observed before the earthquake. Due to large displacement along the plate interface near the trench, geological unit above the plate interface is extension stress state, and the normal faults and open fissures should be ruptured during this earthquake.

Key Words: Great East Japan earthquake, seismic reflection analysis, submersible seafloor observations, fault distributions, tsunami mechanisms

INTRODUCTION

The March 2011 Tohoku-Oki earthquake (Mw 9.0) ruptured a wide area along the plate interface off the Pacific coast of Tohoku, Japan (e.g., Ide et al., 2011). The tsunami induced in the 2011 earthquake was extremely huge (Fujii et al., 2011). However, the estimated tsunami source area (significant seafloor uplifted area) was not so wide (Hayashi et al., 2011; Fujii et al., 2011; Fujiwara et al., 2011; Fig. 1). From the offshore tsunami records, a large plate boundary slip was estimated to be occurred off Miyagi near the trench (Maeda et al., 2011). To reveal mechanisms of the huge tsunami generation, the shallow fault distributions and mechanisms are important to know. Because long-period slip near the trench contributing to the huge tsunami generated almost no energy (Koper et al., 2011), it is difficult to reveal the rupture process near the trench only from onshore seismometer data. Here we identify a series of faults near the trench from a seismic profiles and observe dynamic change of the seafloor trace of fault system from submersible observations before the earthquake (YK08-06 in 2008) and after the earthquake (YK11-04 and YK11-06 in 2011). Because our survey area includes the region where the largest vertical displacement is predicted to have occurred (Fujii et al., 2011; Fig. 1), the shallow faults discussed here are likely to be directly related to the tsunami characteristics.

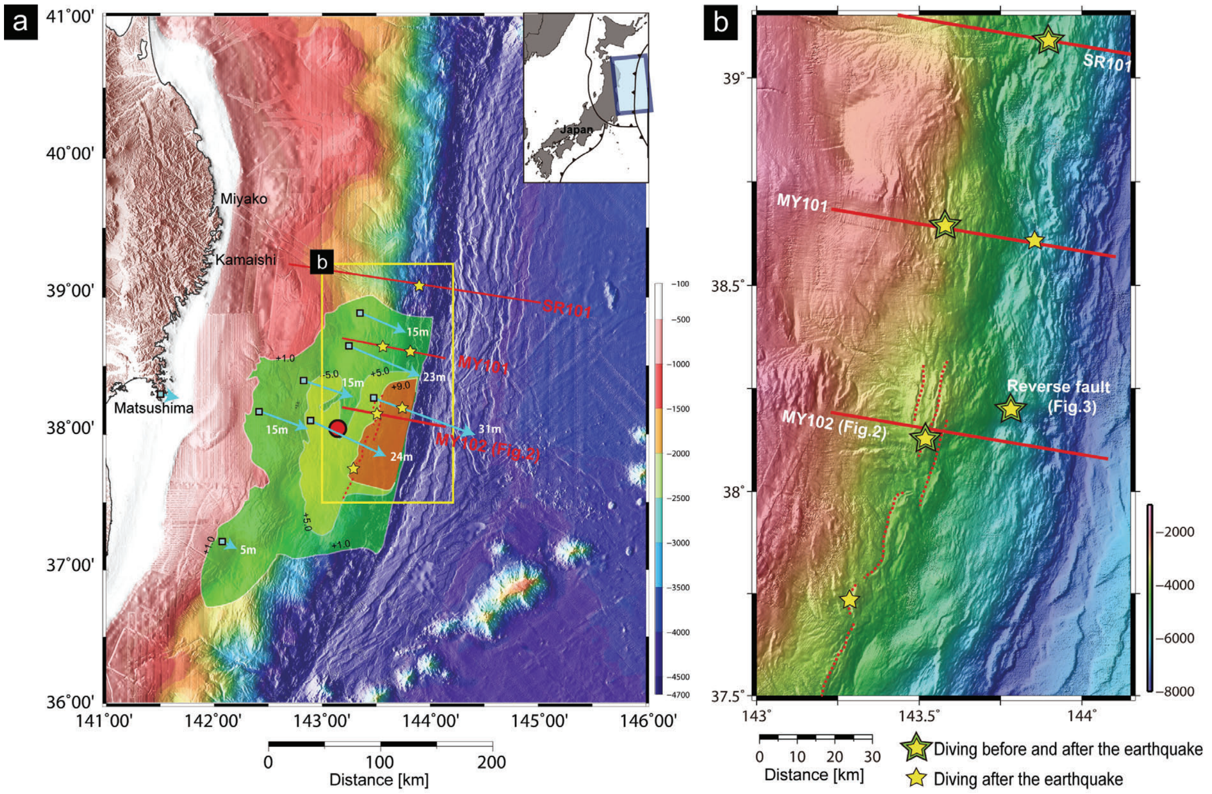

Fig. 1 (a) Index map for 2011 Tohoku Earthquake in the Japan Trench (JCG and JAMSTEC, 2011). Hypoceneter of the mainshock is shown by red circle. Red, yellow and green areas are uplifted regions estimated from tsunami inversion (Fujii et al., 2011). Red lines are the locations of seismic profiles used in this study. Blue arrows indicate dynamic seafloor displacement revealed using seafloor observatories (Sato et al., 2011; Kido et al., 2011). (b) Enlarged map around the diving points (stars). The diving points are on the seismic transects, because we identified fault distribution on the seismic profiles. Red dashed lines indicate the seafloor trance of the normal faults.

FAULT DISTRIBUTION ON SEISMIC PROFILES

Around the huge tsunami source area off Miyagi (Fig. 1), multi-channel seismic reflection data were acquired by R/V Kairei of JAMSTEC (Tsuru et al., 2002). We analyzed this data for an investigation of fault geometry (Tsuji et al., 2011) and conducted submersible observations for the deployment of seafloor observatories for the interpreted fault traces from 2008 (Fig. 2; Ito et al., 2011). We applied conventional seismic processing for the multi-channel seismic data, including trace editing, multiple suppression, deconvolution, velocity analysis, stacking, and post-stack migration. We then obtained the depth-domain profile (Fig. 2) by using stacking velocity (Tsuji et al., 2011). Due to limitation of the streamer length, it was difficult to determine seismic velocities accurately in the deeper lithology.

On the reflection profile acquired at the huge tsunami source area (MY102 in Fig. 1 and Fig. 2), large normal fault maybe connecting to the plate interface and extending toward a seafloor ridge is identified (Tsuji et al., 2011) in addition to several branching faults and backstop interface interpreted as a boundary between seaward accreted sequence and landward less-deformed Cretaceous sequence (von Huene et al., 1994; Tsuru et al., 2002). The displacements along the normal fault offset a Cretaceous sequence surface by ~800 m (Fig. 2c). Because seafloor ridge is also observed due to normal fault displacements (~150m; Fig. 2c), the offset could be generated by accumulation of many earthquake ruptures along the fault. Although we cannot clearly observe the reflection signal from deeper part of the normal fault, the ~800 m total displacements would be possible when the normal fault connects to the plate interface. The seafloor ridges generated by the normal fault are well identified on the seafloor topography and continued parallel to the trench axis (red dashed lines in Fig. 1b). These ridges further become the transition point of seafloor slope angle; seafloor seaward side of the ridge is steep slope compared to the landward side. Therefore, the normal fault should play an important role at the plate convergent margin off Miyagi.

Landward side of the backstop interface, reflection events suggesting underthrusting sequence were observed beneath the interpreted Cretaceous sequence (Fig. 2). This interpreted underthrusting sequence could be less-consolidated sequence, because the P-wave velocity of this unit is lower than that of hanging wall side. Since the soft sediment is covered by the consolidated Cretaceous sequence, the overburden should generate overpressure within this unit. Because of high pore pressure as well as coseismic high pressure pulse (Ranero et al., 2008), these is a possibility that hydrofracturing is occurred within this unit.

On the reflection profile located at northern part of rupture area (Lines SR101 and MY101 in Fig. 1), the fault distribution within the wedge is much different from the profile of Line MY102. Backstop interface as well as subducting sediment can be clearly imaged on these profiles. Furthermore, seaward-dipping normal faults are intensively developed at the seafloor. These normal faults may be generated by gravitational flow. The seafloor topography (Fig. 1b) further indicates several large submarine slides have generated in this northern region (Sasaki, 2004).

DYNAMIC SEAFLOOR DEFORMATION

The seafloor deformation revealed by acoustic GPS (Kido et al., 2011) and positioning of Ocean Bottom Seismometers (Ito et al., 2011) demonstrated that dynamic horizontal seafloor displacement across the normal fault is much changed; the station seaward of the normal fault (~70m) is much moved to seaward direction, compared to the landward side of the fault (~30m) (red arrows in Fig. 2b). The large extension stress between these two stations ($>10^{-3}$; Ito et al., 2011) should be possible when normal fault was ruptured because the dip angle of the normal fault is not so steep (< 50 degree). Tsunami waveform inversion demonstrated the seafloor uplifting was generated near the trench (Fujii et al., 2011; Maeda et al., 2011). Furthermore, the location of normal fault is in good agreement with the landward edge of the large displacement region (Fig. 1). These observations suggest that the wedge-shaped unit between the normal fault and plate boundary fault (seaward side of the normal fault) is significantly moved to seaward direction (Tsuji et al. 2011; Ito et al. 2011). Many normal-fault-type aftershocks in the overriding plate (Asano et al., 2011) also support this interpretation of the normal fault displacement. In addition to the large normal fault located at the seafloor slope break, small normal faults are densely distributed especially at the landward side. These normal faults also worked during this earthquake and contributed to the extension.

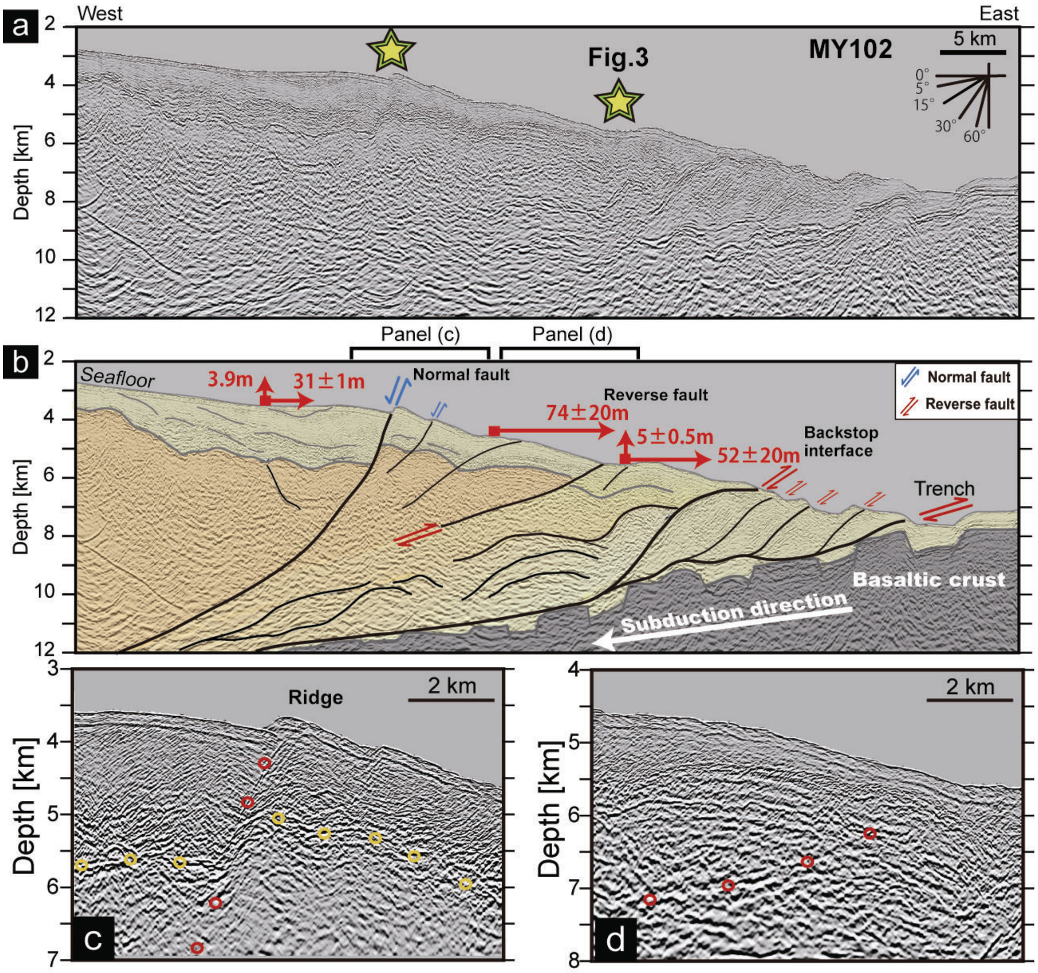

Fig. 2 (a) Original seismic reflection profile with amplitude gain control (AGC). (b) Composite seismic reflection profile with fault interpretations. Red arrows indicate the seafloor displacement derived from seafloor observatories (Ito et al., 2011; Kido et al., 2011). (c) Detailed profile around the 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 reverse fault (red dots). The fault can be identified as a clear reflection.

SEAFLOOR OBSERVATIONS BEFORE AND AFTER THE EARTHQUAKE

Before the earthquake, we used the manned submersible Shinkai 6500 to visit seafloor trances of fault system identified on the reflection profiles (starts in Fig.1; Tsuru et al., 2002; Tsuji et al., 2011). After the earthquake (in June and August 2011), we revisited these previous dive points using Shinkai 6500 and deep-tow camera (YK11-04E and YK11-06E). By comparing the seafloor fault traces before and after the earthquake, we reveal dynamic change of seafloor geometry and environment associated with the 2011 Tohoku earthquake.

Huge landward-dipping normal fault

At the seafloor trace of the normal fault on the seismic line displayed in Fig. 2 (Line MY102), a scarp ~150 m high was observed continuously along the ridge (Tsuji et al., 2011). The slope angle of the scarp is nearly vertical and overhanging in places. Because there is a fresh scarp surface without manganese coating, this scarp may have been generated by recent tectonic activities (Tsuji et al. 2011). We observed and sampled dark consolidated rocks attached to the cliff. This material differed greatly from the poorly consolidated rock composing the cliff in its depositional age. The depositional age of the consolidated rock is 2.4-2.0 Ma (Table 1) and is much older than the reference unconsolidated rock (0.85-0.51 Ma; Tsuji et al., 2011). Furthermore, the physical properties of the consolidated rock are much different from those of the unconsolidated reference rock (Table 1). We suggest that the consolidated rock represents a deeper lithology that was carried to the surface along the fault plane, perhaps during oblique fault displacements. The relation between depositional age and depth suggests that the consolidated rock was uplifted from 100–200 m below the seafloor. However, the P-wave velocity of this rock is much greater than the value expected from the depositional depth (Tsuru et al., 2002). Therefore, the rock adhering to the fault scarp may have been consolidated by dynamic fault activity such as heating or compaction.

When we dived to the same places after the earthquake, diatomaceous soft sediment layers as well as greenish fluffs cover the seafloor at the fault trace. This thick soft sediment seems to be deposited during or after the 2011 earthquake, because the seafloor before the earthquake was covered by gravels collapsed from the scarp. The soft sediments should be derived from landward seafloor slope, because the ridge structure works as a bank for submarine flow sediment (Fig. 2).

The bacterial mats (cold-seeps) were identified at the seafloor trace of southern continuation of the normal fault. Although we have never dived to this position before the earthquake, these bacterial mats could be generated by the dynamic activities of the normal fault in the 2011 earthquake. Furthermore, the heat flow values measured at the seafloor traces of the normal fault (>100mW/m2) are much higher than the background values in this region measured before the earthquake (20~40 mW/m2; Yamano et al., 2008). These observations suggest that intensive fluid flow along the fractures has recently occurred associated with the normal fault activities in the earthquake.

Reverse fault

At the previously interpreted reverse fault (Figs. 2b and 2d), chemosynthetic communities observed along the fault trace before the earthquake (Fig. 3; Tsuji et al., 2011). The post-earthquake seafloor observations (YK11-04E in 2011) demonstrate that several open fissures (1~3 m in width) are developed along the interpreted fault (Fig. 3). These fissures were almost arranged in N-S direction (parallel to trench and fault strike). Because these fissures were not observed before the earthquake, they could rupture during this earthquake event. We have some small earthquakes for the three years (2008 to 2011), but the most presumable reason to form these fissures is the 2011 Tohoku earthquake. We further observed bacterial mattes at a rim of the fissures, suggesting existence of intensive seep along the fissure. Furthermore, dead Calyptogenas were stuck at the open cracks or collapsed under falling rocks, suggesting intensive seafloor sediment flow.

Before the earthquake, we interpreted this fault as reverse type because of its geometry on the seismic profiles (Fig.2; Tsuji et al. 2011). However, we could not find any phenomena for reverse fault type displacement from the post-earthquake seafloor observations.

Table 1. Physical properties and depositional ages of consolidated rock adhering to the fault scarp and reference rock making up the scarp. Velocities were measured at atmospheric pressure.

	Porosity	P velocity	S velocity	Depositional age
Consolidated rock (YK08-06, 1071-R2)	18%	3.6 km/s	2.2 km/s	2.4–2.0 Ma
Reference rock (YK08-06, 1071-R1)	70%	1.6 km/s	---	0.85–0.51 Ma

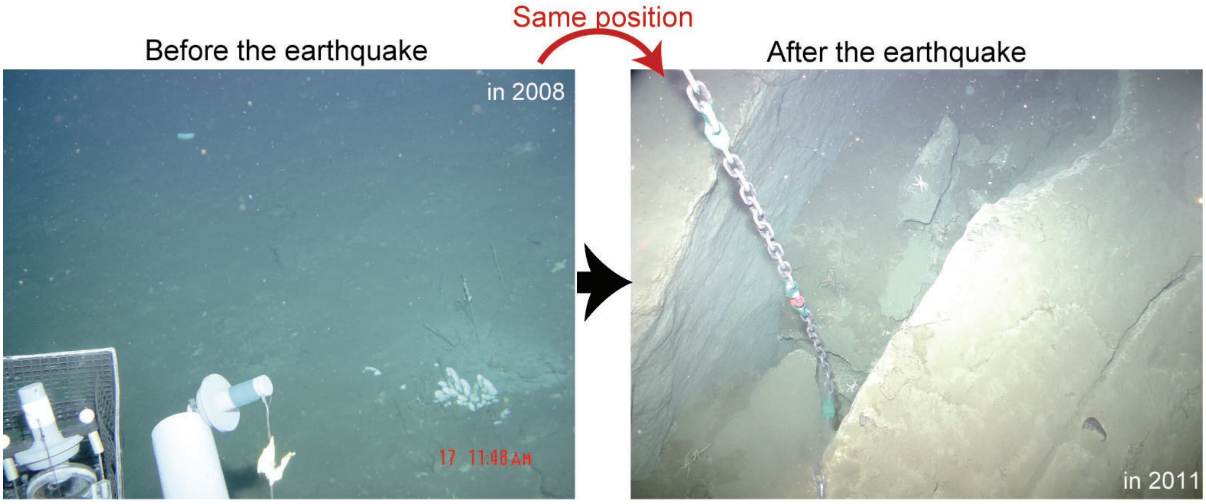

Fig. 3 Seafloor pictures of reverse fault before and after the earthquake. The location of this seafloor is indicated in Figs. 1b and 2a.

Backstop interface

At the backstop interface located at northern edge of the rupture area after the earthquake, we further observed open fissures and bacterial mats. These open fissures were not observed before the earthquake. Because the seafloor seaward side of some fissures is lower than the landward side and because seaward dipping normal faults are observed on the seismic profile acquired at the northern part of rupture area, these fissures could be generated by seafloor gravitational failure. Heat flow values measured after the earthquake at this position (40 – 60 mK/m) are not much higher than the background value in this region measured before the earthquake. Therefore, the earthquake rupture may not propagate to the seafloor along the backstop interface at the northern edge of the rupture area.

Seaward-dipping normal fault

When we dived to seafloor trace of seaward-dipping normal fault where submersible surveys were conducted before the earthquake, we also observed open fissures as well as bacterial mats. Heat flow value measured here (~61 mK/m) was lower than that of the landward dipping normal fault region.

DISCUSSION AND CONCLUSIONS

In the seafloor observations after the earthquake, we observed open fissures in almost all seafloor observation points, suggesting intensive extension near the seafloor associated with large displacement along the plate interface. From the seafloor observations as well as fault distributions on the reflection profiles, we estimate mechanisms of huge tsunami generation (see Fig. 4).

Rupture generated at the plate interface deeper than our seismic profile (hypocenter of this earthquake is ~25 km in depth). In the frequently generated interplate earthquakes, the rupture does not propagate to the trench (Yamanaka and Kikuchi, 2004). Such coseismic slip along the deep plate interface induces smaller seafloor uplift and smaller tsunami (Fig. 4a). In the 2011 Tohoku earthquake, however, the displacement along the plate interface propagated to the trench (Fig. 4b). The reason of rupture propagation to the trench is not clearly understood. The plate boundary slip near the trench is larger than that of deeper fault maybe because of the effect of the dynamic overshoot (Ide et al., 2011). In such a case, geological unit above the plate interface is in extension state (Fig. 4b). Due to the extension, normal faults could be ruptured (Fig. 4c; Tsuji et al., 2011). Many open fissures observed by submersible seafloor observations could also reflect the extension state above the plate interface. Because the normal fault as well as fissures may relax the extension state above the plate interface, they further accelerated the significant plate boundary slip near the trench (50-80m; Fig. 4c). Because the seafloor slope seaward of the normal fault is steeper than landward side, the significant horizontal movement of the steep seafloor near the trench generates significant seafloor uplift and huge tsunami.

Whereas, the submarine sliding of sediment masses (Kawamura et al., 2011) could generate huge tsunami. The seaward-dipping normal faults identified on the profile at the northern side of the rupture area should be developed maybe due to the submarine slide, because the seafloor slope angle is very steep. This event also moved the geological unit to seaward direction and caused tsunami. In this mechanism, large displacement along the plate interface near the trench is not necessary for tsunami generation. Therefore, this mechanism could generate large tsunami (seafloor level change) even in the northern edge of the rupture area.

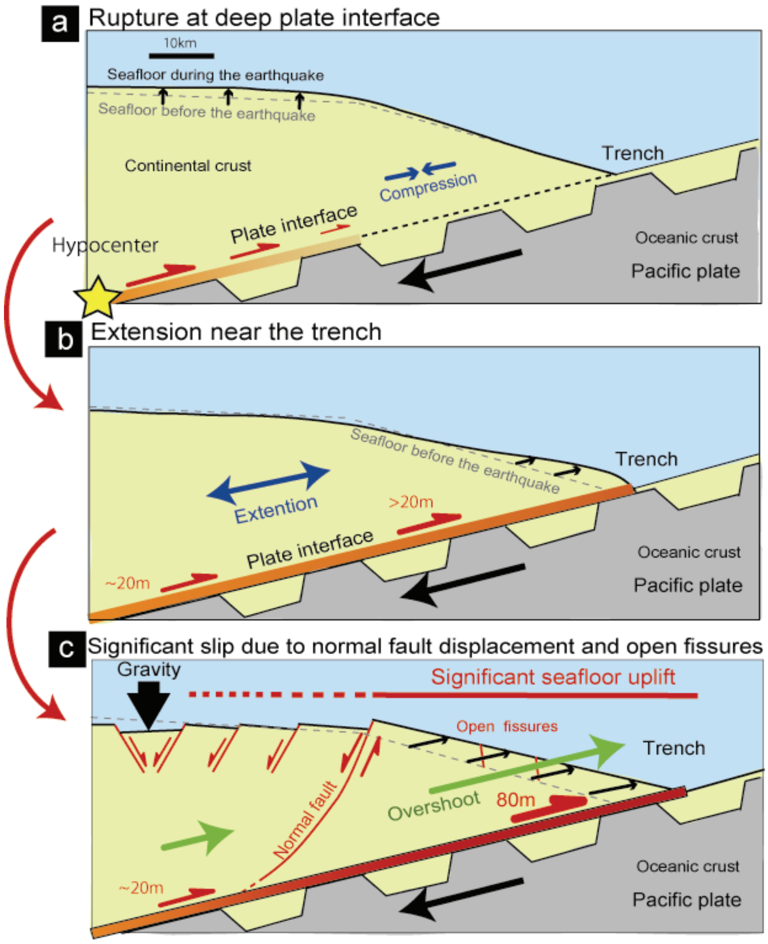

Fig. 4 Schematic image of fault ruptures during the earthquake. Red arrows indicate the fault displacements. Black arrows indicate the seafloor movements which generate tsunami. Blue arrows indicate the stress state within the sedimentary sequence.

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