Correlation of frontal prism structures and slope failures near the trench axis with shallow megathrust slip at the Japan Trench

Yasuyuki Nakamura1, Toshiya Fujiwara2, Shuichi Kodaira1, Seiichi Miura1 & Koichiro Obana1

Since the giant 2011 Tohoku earthquake and tsunami, much research has focused on the distribution of coseismic slip at shallow depths during this subduction megathrust event. Here we present seismic images obtained in the immediate vicinity of the trench axis, that show thrust faults and fold-and-thrust type deformation structures near the epicenter of the 2011 Tohoku earthquake where the large coseismic slip has been inferred, and chaotic structure and the absence of thrust faults in northern and southern source areas. Seismic profiles show evidence of slope failures of the trench inner wall in a proposed tsunami source region around 39°–40° N, where the slips estimated from previous studies are in disagreement. Our results show that structural characteristics in the trench axis may be related to the occurrence of shallow megathrust slip and tsunamigenesis in the Japan Trench.

The giant (M9) 2011 Tohoku earthquake ruptured the plate boundary fault in the Japan Trench subduction zone through the shallowest part of the megathrust, and this shallow slip in particular enhanced the destructive tsunami that followed. Numerous rupture models have been provided to elucidate the characteristics of this giant earthquake using seismological14, geodetic4, and tsunami6 data, and combinations of these6. One distinctive feature is a large (~ 50 m) shallow megathrust slip that occurred at around 38°–38°30′ N. Another characteristic is a proposed tsunami source region at around 39°–40° N, to the north of the large shallow slip area identified by tsunami data analyses4–6. Seafloor geodetic observations7 and estimates of seafloor displacement based on bathymetric datasets8–11 are strong evidence with which to examine the propagation of fault slip towards the seafloor through the trench axis area. Research using differential bathymetry has shown that seafloor displacement during the Tohoku earthquake was > 50 m near the trench axis at 38°05′–38°35′ N, where the large slip occurred during the Tohoku earthquake14, but was not significant outside of this area8,10 (Fig. 1). Interestingly, the displacement estimated from differential bathymetry was not significant near the trench axis at 39°10′–39°30′ N8,10, the area proposed as a northern source region of the tsunami4–6. The structure of deformation within the overriding plate at the toe of the frontal prism near the epicentre is considered an important characteristic for understanding shallow megathrust events such as the Tohoku earthquake6.

Here we present seismic profiles acquired at the immediate vicinity of the Japan trench axis, including those obtained at the same locations as the differential bathymetry estimates. We use these results in combination with seismic profiles in the area near the proposed shallow slip and tsunami source to examine the seismic structure in the vicinity of the trench axis. We find that the structural characteristics seen in the seismic profiles are related to seafloor displacement and possible tsunami generation.

Results
Seismic profiles in the vicinity of the differential bathymetry estimates. The time-migrated seismic profiles clearly reveal detailed structures in the vicinity of the Japan Trench axis, including incoming sediment on the Pacific plate, bending-related normal faults, the oceanic basement, and reverse faults and fold structure within the vicinity of the trench axis. We interpreted these seismic sections in terms of four “seismic units” (SU) following a previous study12, as shown in Fig. 2a–f: SU1 is interpreted as acoustically chaotic frontal

1Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 3173-25 Showa-machi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan. 2Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan. *email: yasu@jamstec.go.jp
Seismic profiles in the northern tsunami source area. Figure 3a–l shows 12 seismic profiles of the trench axis and lowermost landward slope between around 39°12′N and 39°40′N, an area that includes the proposed northern tsunami source region1–6 (see Fig. 1). Although some profiles include sidewipe reflections, in general, all of these profiles show an acoustically chaotic structure and no thrust faults within the sediment near the trench axis. Six profiles (HDSR191, HDSR187, HDSR167, HDSR163, HDSR159, and HDSR155) depict both steep slopes (blue arrows in Fig. 3b,c,h–k) and possible slope failures in the trench inner wall, whereas the other profiles, although they do not show steep slopes, also suggest slope failures. Several seismic profiles, especially lines HDSR175 and HDSR159, also show slump deposits overlying the incoming sediments in the trench axis.

Discussion

Shallow megathrust slip and seismic image in the trench axis. Published rupture models of the 2011 Tohoku earthquake proposed by seismological14, geodetic15, and tsunami1–6 inversions largely agree in placing the largest slip at around 38°–38°30′N. Seismic profile HDMY069 and HD65B (Fig. 2c,d), located at 38°35′N and 38°05′N respectively, displays fold-and-thrust structures imaged within the sediment in the trench axis, where differential bathymetry suggested a large (~50–70 m) trenchward displacement during the Tohoku earthquake12,13. Similarly, folding and thrust faults have been identified near the trench axis at around 37°55′N (HD34B, Fig. 2e), very close to the JFAST drill site C0019, where the coseismic slip was suggested to reach near the trench axis15–17. Three other seismic profiles (Fig. 2a,b,f), located outside of the area with very large shallow slip, display a chaotic acoustic character and no clear thrust faults in the vicinity of the trench axis. The differential bathymetry indicated little or no trench-normal horizontal displacement along these profiles1,6,11.

Seismic profiles along Lines HDMY069, HD65B, and HD34B clearly depict thrust faults as having displaced sediment strata and caused related folding deformation (Fig. 2c–e). Because thrust faults are observed along the differential bathymetry profiles showing large coseismic seafloor displacement (Fig. 2c–e), the imaged thrust faults can be interpreted as the shallowest portions of the plate boundary fault in the trench axis. The seismic profile of Line HDMY069 also depicts a low-angle reflection, interpreted as a thrust fault, within the acoustically chaotic sediment layer (red arrows in Fig. 2e). The existence of this reflection suggests a well-developed thrust fault or fault zone that has a strong enough acoustic impedance contrast to allow it to be imaged against the surrounding chaotic sediments. The high amplitude reflections from strong acoustic impedance contrast may be related to the high pore pressure associated with the fault zone as inferred in the central America17,18.
Figure 2. Seismic profiles with interpretation. Post-stack time-migrated sections, with interpretation shown by colour, along seismic survey lines (a) HDSR179, (b) HDMY143, (c) HDMY069, (d) HD65B, (e) HD34B, and (f) HDFK060 (locations shown in Fig. 1), which correspond to the locations of differential bathymetry estimates. Seismic units SU1 (brown), SU2 (blue), SU3 (yellow), SU4 (green), and TF (grey) are described in the text. Dashed lines indicate normal faults (blue) and thrust faults (red). Red arrows in Fig. 2c indicate a low-angle dipping reflection interpreted as a thrust fault. Vertical exaggeration is 2.5×, assuming a seismic velocity of 1,500 m/s. The seismic profile of HD34B was reproduced from the data published in Ref.12.
Figure 3. Seismic profiles around 39°30’N. Post-stack time-migrated sections with interpretation shown by colour, along seismic lines (a) HDSR195, (b) HDSR191, (c) HDSR187, (d) HDSR183, (e) HDSR179, (f) HDSR175, (g) HDSR171, (h) HDSR167, (i) HDSR163, (j) HDSR159, (k) HDSR155, and (l) HDMY149. Interpreted seismic units are the same as Fig. 2. Profile locations are shown in Fig. 1. Blue arrows indicate steep slopes. Vertical exaggeration is 2.5 ×, assuming a seismic velocity of 1,500 m/s.
Slope failure observed in the northern tsunami source region of the 2011 Tohoku earthquake. The seismic profiles clustered around 39°30′N (Fig. 3a-l) suggest that pervasive slope failure has occurred in the past in this area, which extends at least 40 km along the trench. Seismic sections of lines HDSR159 and HDSR175 in particular show possible slump deposits (Fig. 3f,j) with a horizontal size of ~3 km (Fig. 4) that presumably represent a very recent geological process because they overlie the incoming sediments in the trench. Slumping and slope failure are potentially tsunamigenic22, and a tsunami source near this region has been proposed on the basis of tsunami data analyses from the Tohoku earthquake6,44. A tsunami source in the lower landward slope at around 39°10′N–39°15′N has also been inferred by an analysis of ocean-bottom magnetometer data21 (Fig. 1). A submarine mass failure (SMF) around 39°30′N was proposed as an additional tsunami source to accommodate the high amplitude tsunami waveforms off Iwate, north of the epicentre24. However, based on a detailed review of various studies on the rupture process of the Tohoku earthquake, Lay25 concluded that “an exotic source such as a slump or inelastic deformation is not required to account for the runup (although that possibility cannot be ruled out)”. The amount of the slip along the plate boundary faults has been estimated as ~35 m4, ~25 m5, or 30–40 m6, around 39°30′N by tsunami data analysis. On the other hand, the differential bathymetry indicates that the trenchward horizontal displacement of the lowermost landward slope during the Tohoku earthquake, if any, did not exceed the uncertainty of the estimates. The estimated value was ~29 m at maximum around 39°12′N10, which is comparable to or slightly smaller than the values estimated from tsunami data. Differential bathymetry estimates suggested that the existence of localized very large slip of the megathrust in the shallow part near the trench is unlikely to explain the tsunami source, and the estimated direction of the seafloor shift was mainly trench-parallel and the trench-normal shift was small10. This predominantly trench-parallel shift might have been caused by the broader small uplift in the lower slope10. It is also possible that bathymetric features such as small bumps or valleys caused by slope failures obscured the correlation between the bathymetric data from before and after the earthquake. Taking into account the slope failures imaged in our seismic profiles of this region, we speculate that small–scale slope failure might have contributed to tsunamigenesis during the Tohoku earthquake. Note that no large–scale slope failure associated with the 2011 Tohoku earthquake was identified in the differential bathymetry result in this region, including the area of the proposed SMF22,24. The slope failures observed in this study is located ~20 km trenchward of the area of the proposed SMF24.

Bathymetric data obtained before the 2011 Tohoku earthquake show the presence of slump deposits in this area27 (Fig. 4), so slope failure undoubtedly occurred before the Tohoku earthquake. The acoustically chaotic character of the inner trench hanging wall on some of the seismic sections might be due to repeated slope failures and erosion. The slump deposits observed on the seismic sections and in the bathymetry data were not, at least initially, formed during the Tohoku earthquake, but they might be related to past tsunamis. This area has been suggested to be the source region of the 1896 Meiji Sanriku earthquake and tsunami21,28. Although the estimated large slip (~20 m) region is landward of our survey area28, the observed slump deposit might be related to the 1896 Meiji Sanriku event.

The structure and property of the incoming plate are important controlling factors of the seismogenesis and structural evolution in the subduction zones. A recent study26 found that the post–spreading volcanism altered the structure of the uppermost part of the incoming Pacific plate in the vicinity of the trench axis around 39°N, which corresponds to the area where slope failures were identified in the seismic profiles. Magmatic intrusions and thermal metamorphism associated with post–spreading volcanism were suggested to disturb the smectite–rich pelagic clay layer in incoming sediments, and the subduction of this disturbed area was suggested to prevent giant near–trench interplate coseismic slip in this region26. Most of the seismic profiles around 39°30′N were interpreted to lack the chert layer (SU3) and suggest that the pelagic clay layer was disturbed in the shallow most part of the subduction zone. Seismic profiles (e.g., Fig. 3g–j) show rough basement topography and a small hill–like structure interpreted as post–spreading volcanism (petit–spot, Line HDSR187, Fig. 3c). The absence of the smectite–rich clay around the plate boundary fault could have increased the basal friction27. The increased basal friction could have contributed to building higher critical taper angle and steeper slopes of the frontal prism21. The taper angle estimated from our seismic sections in the small shallow slip area (Fig. 2a,h,f) is approximately 60% higher than that in the large shallow slip area (Fig. 2c–e) on average, assuming 1.8–2.1 km/s as the P wave velocity within the hanging wall sediments32,33. The subduction of the basement with rough topography might have also caused the steep inner trench slopes. The steeper slopes could have caused slope failures observed in this region. The taper angles in the Japan Trench were also estimated using regional–scale seismic profiles44. The area of seamount subduction has a larger taper angle34, which is in good agreement with our study.
Figure 4. Bathymetry around 39°30′N. Shaded bathymetric map generated from compiled pre-earthquake bathymetric data. Locations of the seismic sections shown in Fig. 3 are also indicated. Yellow dashed lines delineate slump bodies that were also identified on the corresponding seismic sections. The map was created with GMT-4.5.7 (https://www.generic-mapping-tools.org/).
Summary
Various studies have shown that the large shallow plate boundary slip during the Tohoku earthquake occurred in the central part of the Japan Trench but did not occur in other parts. Seismic profiles near the Japan Trench axis acquired in the vicinity of the differential bathymetry estimates show that the difference in the amount of the shallow slip during the earthquake corresponds to different characteristic structures in the trench axis. Profiles in areas with large slip display folds and thrust faults, whereas ones in areas without large slip display chaotic acoustic structures in the trench axis without any clearly imaged thrust faults or folding deformation. The deformation structures created by thrust faults in the trench axis may thus be related to large shallow slip of the plate boundary fault during the 2011 Tohoku earthquake. The faults moved the hanging wall, and its displacement was observed in the differential bathymetry data. In the area near a proposed tsunami source at around 39°–40° N, seismic profiles and bathymetry data show slump deposits, suggesting that slope failures have occurred in the past. Considering the slip estimation from tsunami and differential bathymetry data, we speculated that small-scale slope failure might have contributed to tsunamigenesis during the 2011 Tohoku earthquake. Observations in the northern tsunami source area could be related to the subduction of incoming plate altered by post-spreading volcanism, which could increase the basal friction of the frontal prism caused by the absence of the basal input sediments.

Methods
The seismic dataset used in this study was collected during cruise KR13-11 of R/V Kairei in 2013 and cruise KY15-14 of R/V Kaiyo in 2015. A digital streamer cable with 168–192 channel hydrophones at 6.25 m intervals, towed at 6 m depth, recorded seismic signals from an array of airguns (6.23 L) towed at 5 m depth. The data were sampled at 1 ms intervals, and airguns were fired every 37.5 m with 13.8 MPa of air pressure. We obtained the best time-migrated images from the recorded data by using conventional procedures described in Ref.24.

Data availability
The seismic data used in this paper are available from the Japan Agency for Marine-Earth Science and Technology (http://www.jamstec.go.jp/obsmcs_db/e/).

Received: 13 December 2019; Accepted: 24 June 2020
Published online: 14 July 2020

References
1. Ide, S., Balsey, A. & Beroza, G. C. Shallow dynamic oversoot and energetic deep rupture in the 2011 Mw 9.0 Tohoku-Oki earthquake. Science 332, 1426–1429 (2011).
2. Lay, T., Ammon, C. J., Kanamori, H., Xue, L. & Kim, M. J. Possible large near-trench slip during the 2011Mw 9.0 off the Pacific coast of Tohoku Earthquake. Earth Planets Space 63, 687–692 (2011).
3. Iinuma, T. et al. Coseismic slip distribution of the 2011 off the Pacific Coast of Tohoku Earthquake (M9.0) refined by means of seafloor geodetic data. J. Geophys. Res. Solid Earth 117, B07409 (2012).
4. Satake, K., Fujii, Y., Harada, T. & Namegaya, Y. Time and space distribution of coseismic slip of the 2011 Tohoku earthquake as inferred from Tsunami waveform data. Bull. Seismol. Soc. Am. 103, 1473–1492 (2013).
5. Hossen, M. J., Cummins, P. R., Dettmer, J. & Baba, T. Tsunami waveform inversion for sea surface displacement following the 2011 Tohoku earthquake: Importance of dispersion and source kinematics. J. Geophys. Res. Solid Earth 120, 6452–6473 (2015).
6. Koketsu, K. et al. A unified source model for the 2011 Tohoku-Oki earthquake. Earth Planet. Sci. Lett. 310, 480–487 (2011).
7. Ito, Y. et al. Frontal wedge deformation near the source region of the 2011 Tohoku-Oki earthquake. Geophys. Res. Lett. 38, L00G05 (2011).
8. Fujiwara, T., Kodaira, S., No, T., Kaicho, Y. & Takahashi, N. The 2011 Tohoku-oki Earthquake: displacement reaching the trench axis. Science 334, 1240 (2011).
9. Kodaira, S. et al. Coseismic fault rupture at the trench axis during the 2011 Tohoku-Oki earthquake. Nat. Geosci. 5, 646–650 (2012).
10. Fujiwara, T. et al. Seafloor displacement after the 2011 Tohoku-oki earthquake in the northern Japan Trench examined by repeated bathymetric surveys. Geophys. Res. Lett. 44, 11833–11839 (2017).
11. Kodaira, S., Fujiwara, T., Fujie, G., Nakamura, Y. & Kanamatsu, T. Large coseismic slip to the trench during the 2011 Tohoku-Oki earthquake. Annu. Rev. Earth Planet. Sci. 48, 321–343 (2020).
12. Nakamura, Y., Kodaira, S., Miura, S., Regalla, C. & Takahashi, N. High-resolution seismic imaging in the Japan Trench axis area off Miyagi, northeastern Japan. Geophys. Res. Lett. 40, 1713–1718 (2013).
13. Chester, F. M. et al. Structure and composition of the plate-boundary slip zone for the 2011 Tohoku-Oki earthquake. Science 342, 1208–1211 (2013).
14. Ujiie, K. et al. Low coseismic shear stress on the Tohoku-Oki megathrust determined from laboratory experiments. Science 342, 1211–1214 (2013).
15. Fulton, P. M. et al. Low coseismic friction on the Tohoku-Oki fault determined from temperature measurements. Science 342, 1214–1217 (2013).
16. Expedition 343/343T Scientists. Site C0019. In Proc. IODP (eds. Chester, F. M., Mori, J., et al.) Vol. 343/343T https://doi.org/10.2204/iodp.proc.343343T.103.2013 (Integrated Ocean Drilling Program Management International, Inc., 2013).
17. Bangs, N. L. B., Shipley, T. H., Moore, J. C. & Moore, G. F. Fluid accumulation and channeling along the northern Barbados Ridge decollement thrust. J. Geophys. Res. Solid Earth 104, 20399–20414 (1999).
18. Ranero, C. R. et al. Hydrogeological system of erosional convergent margins and its influence on tectonics and interplate seismogenesis. Geochem. Geophys. Geosyst. 9, Q03S04 (2008).
19. Park, J.-O. A deep strong reflector in the Nankai accretionary wedge from multichannel seismic data: Implications for underplating and interseismic shear stress release. J. Geophys. Res. Solid Earth 107, ESE 3-1–ESE 3-16 (2002).
20. Ujiie, K. et al. Broad, weak regions of the Nankai megathrust and implications for shallow coseismic slip. Earth Planet. Sci. Lett. 284, 44–49 (2009).
21. Tanioka, Y. & Seno, T. Sediment effect on tsunami generation of the 1896 Sanriku tsunami earthquake. Geophys. Res. Lett. 28, 3389–3392 (2001).
22. Schnyder, J. S. D. et al. Tsunamis caused by submarine slope failures along western Great Bahama Bank. Sci. Rep. 6, 35925 (2016).
23. Ichihara, H., Hamano, Y., Baba, K. & Kasaya, T. Tsunami source of the 2011 Tohoku earthquake detected by an ocean-bottom magnetometer. Earth Planet. Sci. Lett. 382, 117–124 (2013).
24. Tappin, D. R. et al. Did a submarine landslide contribute to the 2011 Tohoku tsunami? Mar. Geol. 357, 344–361 (2014).
25. Lay, T. A review of the rupture characteristics of the 2011 Tohoku-oki Mw 9.1 earthquake. Tectonophysics 733, 4–36 (2018).
26. Yamazaki, Y., Cheung, K. F. & Lay, T. A self-consistent fault slip model for the 2011 Tohoku earthquake and tsunami. J. Geophys. Res. Solid Earth 123, 1435–1458 (2018).
27. Hydrographic and Oceanographic Department, Japan Coast Guard and JAMSTEC. Compilation of Tohoku-oki bathymetric data before the 2011 Tohoku-oki earthquake (in Japanese). Seismol. Soc. Jpn. News Lett. 23(2), 35–36 (2011).
28. Tanioka, Y. & Satake, K. Fault parameters of the 1896 Sanriku tsunami earthquake estimated from tsunami numerical modeling. Geophys. Res. Lett. 23, 1549–1552 (1996).
29. Satake, K., Fujii, Y. & Yamaki, S. Different depths of near-trench slips of the 1896 Sanriku and 2011 Tohoku earthquakes. Geosci. Lett. 4, 33 (2017).
30. Fujie, G. et al. Spatial variations of incoming sediments at the northeastern Japan arc and their implications for megathrust earthquakes. Geology 48, 614–619 (2020).
31. Davis, D., Suppe, J. & Dahlen, F. A. Mechanics of fold-and-thrust belts and accretionary wedges. J. Geophys. Res. 88, 1153–1172 (1983).
32. Tsuru, T. et al. Tectonic features of the Japan Trench convergent margin off Sanriku, northeastern Japan, revealed by multichannel seismic reflection data. J. Geophys. Res. Solid Earth 105, 16403–16413 (2000).
33. Nakamura, Y. et al. Seismic imaging and velocity structure around the JFAST drill site in the Japan Trench: low Vp, high Vp/Vs in the transparent frontal prism. Earth Planets Space 66, 121 (2014).
34. Koge, H. et al. Friction properties of the plate boundary megathrust beneath the frontal wedge near the Japan Trench: an inference from topographic variation. Earth Planets Space 66, 153 (2014).
35. Wessel, P., Smith, W. H. F., Scharroo, R., Luis, J. F. & Wobbe, F. Generic mapping tools: improved version released. EOS Trans. AGU 94(45), 409–410 (2013).

Acknowledgements
We are grateful to Dr. N. Cubas and two anonymous reviewers for their helpful comments and suggestions. The other two anonymous reviewers for the previous version of the manuscript significantly helped to improve the quality of the manuscript. We thank captains Hitoshi Tanaka and Yoshiyuki Nakamura and their respective crews for their help during the seismic cruises. We thank Makoto Ito and colleagues at Nippon Marine Enterprises Ltd. for their technical support during data acquisition and preliminary data processing. Part of this study was supported by a Grant-in-Aid for Specially Promoted Research from the Japan Society for Promotion of Science (JSPS KAKENHI Grant Number JP26000002). Figures 1 and 4 were made with Generic Mapping Tools software35.

Author contributions
Y.N. participated in the seismic surveys as the chief scientist, processed the seismic data, and wrote the manuscript. Y.N. and S.K. interpreted the seismic profiles. T.F. participated in the Sonne cruise and processed the bathymetric data. S.K. and S.M. coordinated the seismic surveys. K.O. participated in seismic cruise KY15-14. All authors discussed the contents of the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to Y.N.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2020