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Spatial variations of incoming sediments at the northeastern Japan arc and their implications for megathrust earthquakes

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ABSTRACT

The nature of incoming sediments is a key controlling factor for the occurrence of megathrust earthquakes in subduction zones. In the 2011 M_w 9 Tohoku earthquake (offshore Japan), smectite-rich clay minerals transported by the subducting oceanic plate played a critical role in the development of giant interplate coseismic slip near the trench. Recently, we conducted intensive controlled-source seismic surveys at the northwestern part of the Pacific plate to investigate the nature of the incoming oceanic plate. Our seismic reflection data reveal that the thickness of the sediment layer between the seafloor and the acoustic basement is a few hundred meters in most areas, but there are a few areas where the sediments appear to be extremely thin. Our wide-angle seismic data suggest that the acoustic basement in these thin-sediment areas is not the top of the oceanic crust, but instead a magmatic intrusion within the sediments associated with recent volcanic activity. This means that the lower part of the sediments, including the smectite-rich pelagic red-brown clay layer, has been heavily disturbed and thermally metamorphosed in these places. The giant coseismic slip of the 2011 Tohoku earthquake stopped in the vicinity of a thin-sediment area that is just beginning to subduct. Based on these observations, we propose that post-spreading volcanic activity on the oceanic plate prior to subduction is a factor that can shape the size and distribution of interplate earthquakes after subduction through its disturbance and thermal metamorphism of the local sediment layer.

INTRODUCTION

The occurrence and magnitude of thrust earthquakes in subduction zones is closely linked to interplate seismic coupling. This coupling, in turn, is generally thought to be related to the surface topography and surface materials that form the incoming oceanic plate. Large geometrical irregularities like seamounts tend to hinder long-range coseismic rupture propagation (Wang and Bilek, 2014). In contrast, thick sediments can smooth out low seafloor relief and result in a homogenized interplate coupling (e.g., Ruff, 1989).

Fault zone materials control the mechanical behavior of a plate boundary fault. For example, results from the Integrated Ocean Drilling Program (IODP) Expedition 343 after the 2011 M_w 9 Tohoku earthquake (offshore Japan) showed that the giant coseismic slip near the trench (>50 m) occurred within a thin smectite-rich clay layer at the plate boundary (Chester et al., 2013). Because smectite is an extremely weak mineral whose presence can dramatically change both the static and dynamic friction along a fault, the presence of an ultraweak smectite-rich clay layer is now thought to be a prerequisite for giant coseismic slip (Ujiie et al., 2013) like that observed at Tohoku. Incoming sediments of the northwestern Pacific plate are generally divided into three parts: the lowermost sediments are a chert unit, overlain by thin pelagic red-brown sediments, with the top unit a thick hemipelagic sediment layer (Shipboard Scientific Party, 1980; Moore et al., 2015). Mineralogical analyses of drilling cores from both IODP Expedition 343 (post-subduction) and Deep Sea Drilling Project Site 436 (pre-subduction) show that the origin of smectite at the plate boundary fault is from pelagic red-brown clay within the incoming sediments (Kameda et al., 2015; Moore et al., 2015). Thus, the composition of incoming sediments is also a key factor shaping the occurrence of megathrust earthquakes.

In the past, due to relatively poor seismic coverage, spatial variations in incoming sediments have not been well constrained. Recently, we conducted intensive multichannel seismic (MCS) reflection surveys and wide-angle seismic reflection and refraction surveys on the northwestern part of the Pacific plate with the goal of revealing the nature of the subduction inputs to the northeastern Japan arc (Fig. 1A). In this study, we present an improved picture of the spatial variations in incoming sediments and discuss its implications for subduction zone earthquakes.

DATA ACQUISTION

Since 2009, we have conducted extensive controlled-source seismic surveys, along lines as much as several hundred kilometers long, that mainly focus on the impact of plate bending–related faulting prior to subduction (Fujie et al., 2013, 2018; Kodaira et al., 2014) (Fig. 1A, thick black lines). MCS data were collected by towing a 6-km-long, 444-channel hydrophone streamer cable and using the large tuned airgun array of R/V *Kairei* of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC; Yokohama, Japan) (total volume of 7800 in^3). The tow depths of the airgun array and the streamer cable were 10 and 12 m, respectively (see the GSA Data Repository[1] for methodology).

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[1] GSA Data Repository item 2020180, additional MCS reflection profiles and representative OBS record sections, as well as methodology, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org. The data used in this study can be accessed through JAMSTEC (http://www.jamstec.go.jp/obsmcs_db/e/index.html).

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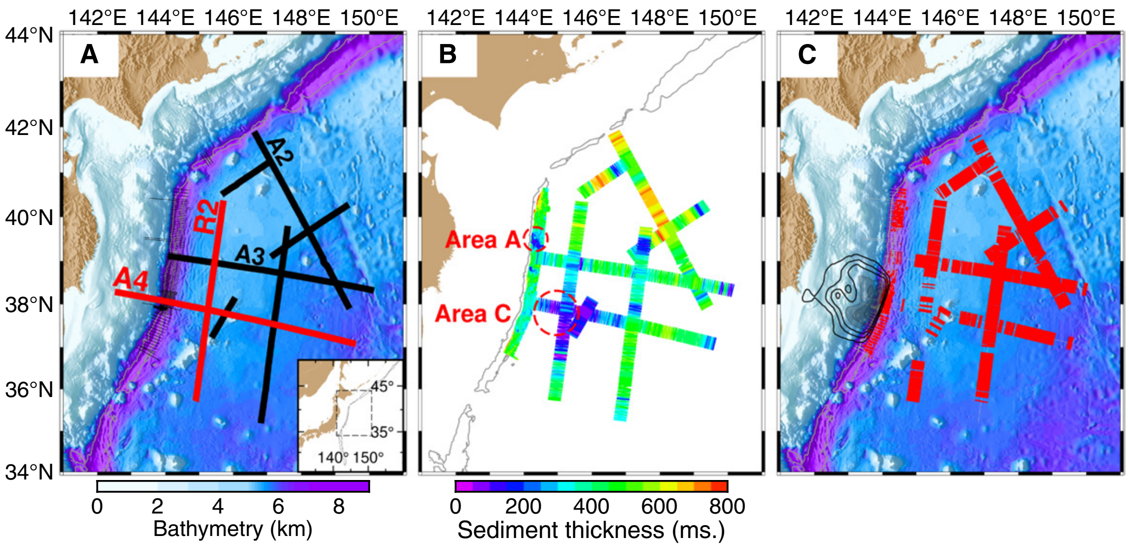

Figure 1. (A) Seismic survey lines in the northwestern Pacific margin (offshore Japan). (B) Sediment thickness in two-way traveltime along multichannel seismic (MCS) lines. Red circles show petit-spot volcanism cluster sites, where many small and young volcanoes are observed (Hirano et al., 2006). Petit-spot sites A and C correspond to apparent thin sediment cover. Most other thin-sediment areas correspond to seamounts and small seafloor bulges. (C) Coseismic slip distribution of the 2011 Tohoku earthquake (black contours) (Iinuma et al., 2012). Contour interval is 10 m, and shaded area represents large-slip (>30 m) area. Distribution of chert unit along MCS lines is plotted in red.

After the 2011 Tohoku earthquake, we also conducted another type of seismic survey that focused on the traces of giant coseismic slip near the trench (Kodaira et al., 2012; Nakamura et al., 2013). We used a small-offset MCS system (1.2-km-long, 192-channel hydrophone streamer cable, total airgun array volume of 380 in^3) and collected data along >100 densely aligned short survey lines across the Japan Trench (Fig. 1A, thin black lines). Tow depths of the airguns and streamer cable were relatively shallow (5 m and 6 m, respectively) to better focus on the sedimentary structure. Despite significant differences in the survey configuration, spatial variations in sediment thickness are well constrained by both surveys after applying standard post-stack time migration (Figs. 2 and 3).

RESULTS

Spatial Variations in Sediment Thickness

We define the sediment thickness by its associated two-way traveltime between the seafloor and acoustic basement. Acoustic basement is a seismic reflector with a large amplitude beneath the seafloor, usually corresponding to the top of the basaltic crust. Our MCS data show that sediment thicknesses typically are 300–500 ms (Fig. 1B), corresponding to 240–400 m for an average seismic velocity within the sediments of 1.6 km/s (Shipboard Scientific Party, 1980). Typical sediment thicknesses are generally consistent with those determined in a previous study (Divins, 2003), but we found a few areas where the sediments are observed to be extremely thin, such as areas A and C in Figure 1B.

As described above, the base of the sediments in this region is generally a chert unit formed of lithified pelagic siliceous sediments. The top and bottom interfaces of the chert unit are commonly reflective, and there commonly exist patchy reflective zones between them (Shipboard Scientific Party, 1980) (Fig. 2C). However, in the thin-sediment areas, we do not observe the characteristic appearance of the chert unit (Fig. 2D). The absence of the chert unit implies that the lower part of the sediments, including the pelagic red-brown clay, is missing because the chert unit is the lowermost part of the sediments and the the clay layer is located immediately above the chert (Moore et al., 2015). We carefully investigated all MCS profiles and mapped areas where we could clearly recognize the characteristic appearance of the chert unit. We confirm a good correlation between sediment thickness and the distribution of the chert unit, which suggests that the pelagic clay is missing in the thin-sediment areas (Fig. 1C).

P-Wave Velocity Beneath the Acoustic Basement

In thin-sediment areas, some reflectors beneath the acoustic basement are also observed (Fig. 2D). We interpret this to mean that the acoustic basement might not be the top of the intact basaltic oceanic crust in these regions. To further investigate the nature of the acoustic basement, we utilize wide-angle seismic survey data.

In 2014 and 2015, we deployed 88 ocean-bottom seismometers (OBSs) of JAMSTEC and GEOMAR (Kiel, Germany) at intervals of 6 km along line A4 (Fig. 1A) and fired the airgun array of R/V *Kairei*. We determined a two-dimensional (2-D) P-wave velocity (Vp) model by traveltime inversion (Fujie et al., 2013, 2016, 2018) using both OBS and MCS data (see the Data Repository). This Vp model indicates a simple layered oceanic plate structure (Fig. 2E). To show lateral variations within the crust, we extract one-dimensional (1-D) Vp-depth profiles from the 2-D Vp model every 10 km and categorize them as belonging to three possible segments: (1) the bend fault segment, where a horst-and-graben structure caused by bend faulting is observed; (2) the thin-sediment segment, where sediments appear to be extremely thin (area C of Fig. 1B); and (3) the thick-sediment segment (Figs. 2E and 2F).

In general, the oceanic crust in the northwestern Pacific plate consists of upper crust (oceanic layer 2, with large Vp gradient) and lower crust (oceanic layer 3, with almost constant Vp). All 1-D Vp profiles are basically consistent with this general structure, but there are intriguing differences among segments.

The oceanic crust in the thick-sediment segment is considered to be "standard" in this region because Vp and its gradient are consistent with those of flat-ocean-floor parts of nearby survey lines A2 and A3 (Fujie et al., 2018). In the bend fault segment, the Vp of crust and mantle are significantly lower than in the thick-sediment segment. The Vp reduction near the trench is observed in nearby survey lines A2 and A3, as well as at many other subduction trenches around the world (e.g., Van Avendonk et al., 2011; Shillington et al., 2015; Grevemeyer et al., 2018). This has been explained as a consequence of bend faulting.

In the thin-sediment segment, lower-crustal Vp is basically the same as in the thick-sediment segment. In contrast, Vp immediately beneath the acoustic basement is the lowest of the three segments. In addition, the boundary between oceanic layers 2 and 3, represented by changes in Vp gradient, is a few hundred meters deeper than in other segments, indicating that the upper-crustal thickness is a little thicker than in the other segments.

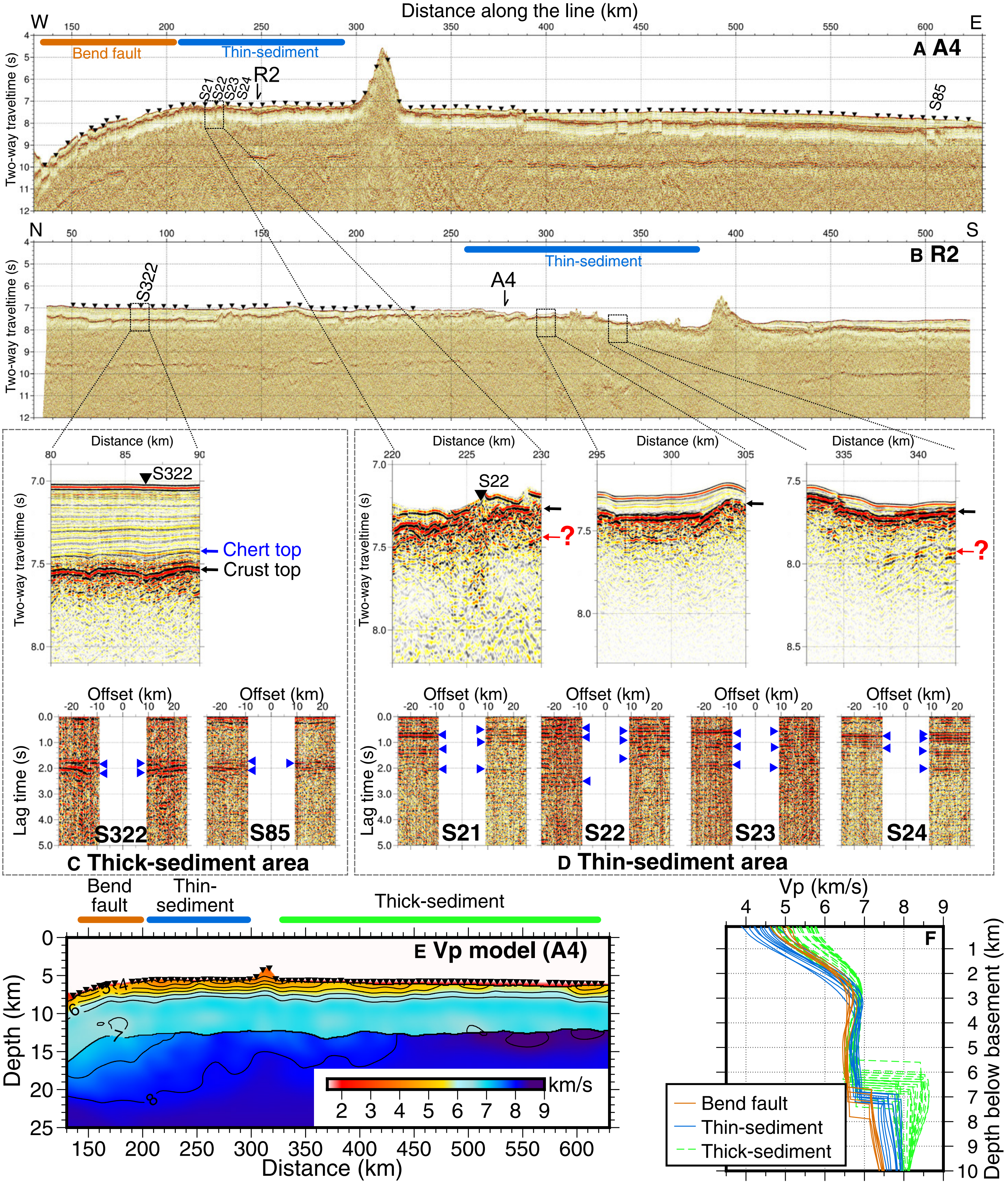

Figure 2. (A,B) Time-migrated multichannel seismic (MCS) reflection profiles of seismic survey lines A4 and R2 (northeastern Japan arc; see Fig. 1A for location). Thin-sediment area corresponds to petit-spot volcanism site C (Fig. 1B). Inverted triangles show ocean-bottom seismometer (OBS) positions. (C,D) (Top) Enlarged MCS profiles. Black arrows indicate acoustic basement; red arrows indicate sub-acoustic basement reflector. (Bottom) Receiver function of OBS data. Triangles indicate P-wave to S-wave conversion interfaces. (E) P-wave velocity (Vp) model determined by traveltime inversion. (F) One-dimensional Vp-depth profiles along line A4, sampled every 10 km horizontal distance.

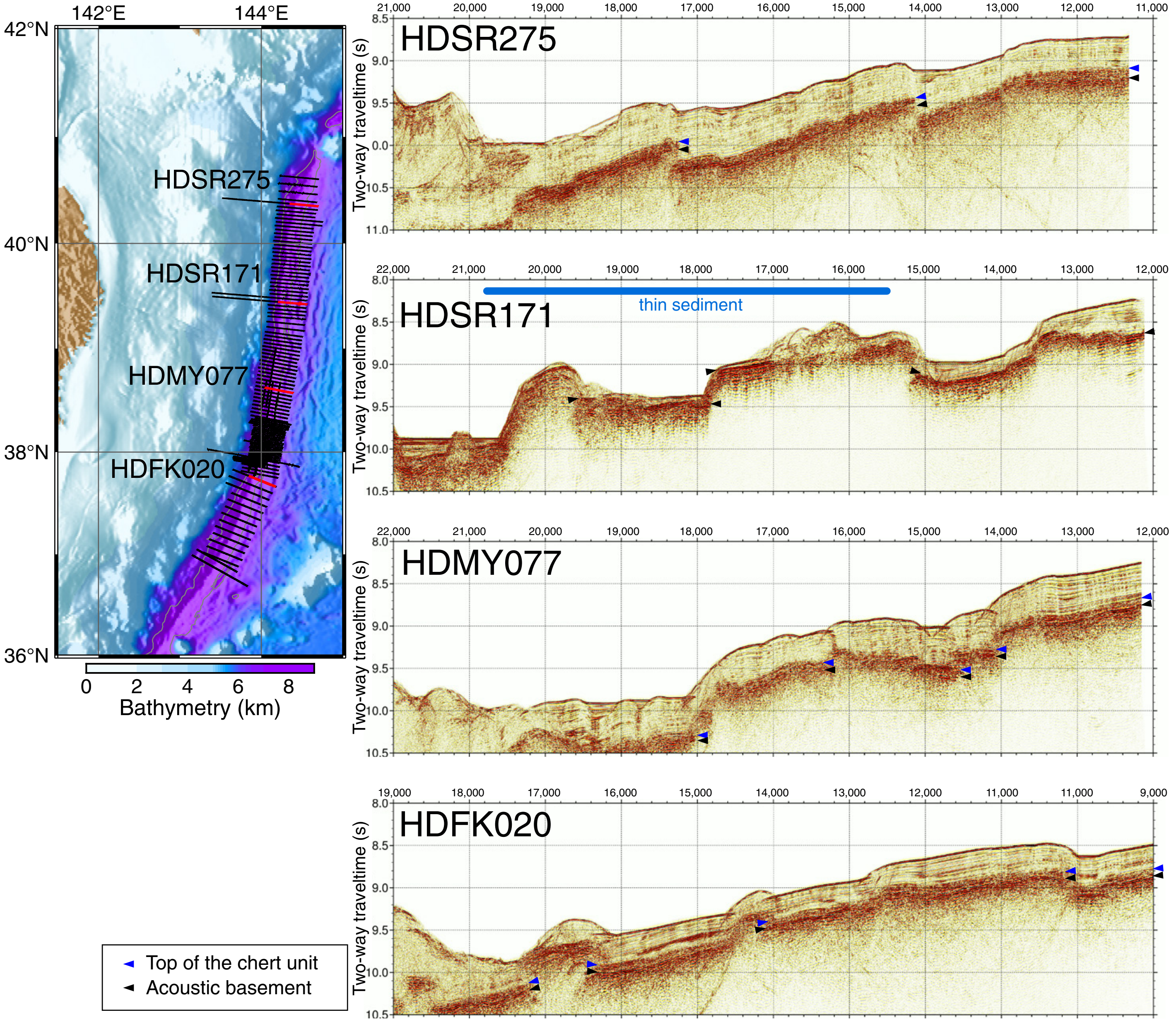

Figure 3. Time-migrated multichannel seismic (MCS) reflection profiles near the trench (northeastern Japan arc) obtained by the small-offset MCS system. Horizontal axis is CDP (Common Depth Point; CDP spacing is 3.125 m). The sediment is roughly 400–500 ms (two-way traveltime) along most lines, but in thin-sediment area A (profile HDSR171; Fig. 1B), it is much thinner.

P-S Conversion Interfaces at Approximately the Depth of the Acoustic Basement

We also calculated receiver functions (RFs) to investigate in more detail the structure immediately beneath the acoustic basement. RFs are an effective tool for detecting P-wave to S-wave (P-S) conversion interfaces (e.g., Vinnik, 1977). The advantage of applying RFs to controlled-source data is that we can choose the imaging target depth by limiting the offset distance. We chose an offset range of 9–25 km to highlight the depth of the sediment-crust boundary.

In thick-sediment areas, a single P-S conversion interface was imaged at ~2 s lag time (Fig. 2C). This is interpreted to be acoustic basement, corresponding to the top of the oceanic crust. In contrast, in the thin-sediment segment (Fig. 2D), we observed multiple P-S conversion interfaces between 0 and 2 s. The top P-S conversion interface is interpreted to be the acoustic basement, and the others appear to be located immediately beneath it.

DISCUSSION

Tectonic Processes Forming Thin-Sediment Areas

In the northwestern Pacific, many young (1–10 Ma), small monogenetic volcanoes, called petit-spot volcanoes, have been found in clusters (Hirano et al., 2006) on the incoming plate where it approaches the trench. The thin-sediment areas A and C (Fig. 1B) correspond to petit-spot cluster sites A and C of Hirano et al. (2006), respectively. This good correlation implies that apparent thinning of the sediments is likely to be associated with this post-spreading volcanic activity.

Ohira et al. (2018) carefully investigated Vp models derived from airgun-OBS data near area C and showed that the low Vp beneath acoustic basement in area C cannot be explained by bend faulting or preexisting ancient tectonic features. Instead they concluded that the low Vp is associated with petit-spot volcanism. Hirano et al. (2006) pointed out that dredge samples from petit-spot volcanoes show similar chemical

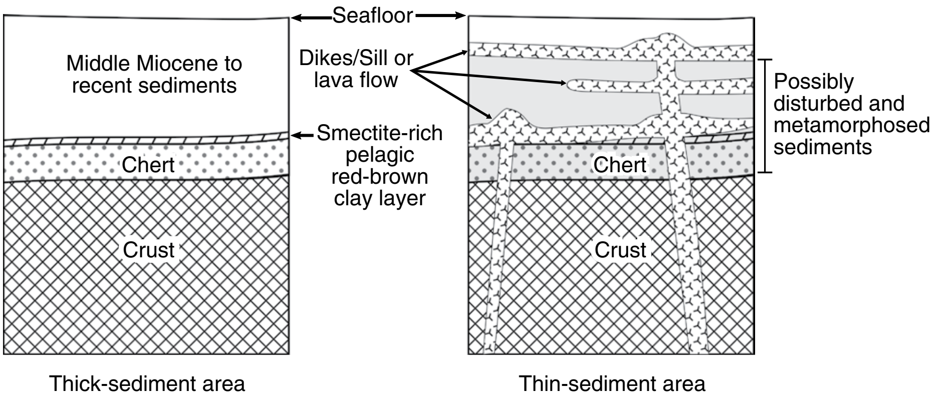

Figure 4. Schematic diagram of sedimentary structure at the northwestern Pacific plate. (Left) Thick-sediment area, based on Deep Sea Drilling Project data (Shipboard Scientific Party, 1980; Moore et al., 2015). (Right) Thin-sediment area, based on our results. Acoustic basement here is proposed to be reflection from magmatic intrusions. The lower part of the sediments, including the smectite-rich pelagic clay layer, is interpreted to have been heavily disturbed and metamorphosed by recent magmatic intrusions.

compositions to those of the Hawaiian north arch where a >100-km-wide area is covered by extensive sheet flows of alkalic basalt, and proposed that sills and dikes have frequently intruded into sediments in petit-spot areas. A potential fossil outcrop of a petit-spot volcano in Central America supports this interpretation (Buchs et al., 2013).

Based on these previous studies and our observations, we propose that the acoustic basement in thin-sediment areas is not the top of the basaltic crust, but instead an apparent basement related to recent petit-spot–related magmatic intrusions (Fig. 4). Multiple P-S conversion interfaces in the thin-sediment segment suggest pervasive magmatic intrusions within the sediments, with the topmost magmatic intrusion (the apparent basement) masking seismic reflections beneath it. We conclude that recent volcanic activity related to petit-spot volcanoes is the origin of the apparent thinness of the sediment layer in these regions.

Implications for Subduction Zone Earthquakes

Pervasive magmatic intrusions should alter the nature of sediments. First, feeder dikes would cut the layered sediments, and magmatic intrusions would disturb preexisting stratigraphy. This should cause the horizontal continuity of the sediments to be reduced. Because chert is a hard siliceous sediment that has a significantly different mechanical behavior from the soft sediments above it, magmas might be likely to intrude just above the chert unit and disturb the smectite-rich pelagic clay layer that is the origin of the smectite along the plate boundary fault. Second, such magmatism within sediments should promote thermal metamorphism of surrounding sediments. Because smectite easily transforms into illite at relatively low temperatures on the order of ~100 °C (Pytte and Reynolds, 1989) and illite has a significantly larger friction coefficient than smectite (Saffer and Marone, 2003), subduction of petit-spot areas would induce regional variations in friction along the plate boundary fault through spatially patchy illitization of the smectite-rich pelagic clay layer.

Area A (Fig. 1B), one thin-sediment area related to the petit-spot volcanism, is currently just entering into the Japan trench at ~39°N. The giant near-trench coseismic slip of the 2011 Tohoku earthquake did not propagate beyond 39°N according to most coseismic slip distribution models derived from seismic and geodetic data (e.g., Ide et al., 2011; Iinuma et al., 2012; Lay, 2018). Based on this correlation (Figs. 1B and 1C), we propose that magmatic intrusions and thermal metamorphism associated with petit-spot volcanism disturbed the smectite-rich pelagic clay layer in incoming sediments, and that the subduction of this disturbed area in turn prevented giant near-trench interplate coseismic slip from propagating further northward. In other words, the decrease in smectite or disturbance of the smectite-rich pelagic clay layer by magmatic intrusions could have played a critical role in arresting coseismic slip propagation during the 2011 Tohoku earthquake.

Because petit-spot clusters are considered to be ubiquitously distributed on the oceanic Pacific plate (Machida et al., 2015), there are likely many other already-subducted petit-spot sites. Although most smectite is transformed into illite at depths >~20 km due to elevated temperature (Peacock and Wang, 1999), petit-spot–related magmatic intrusions within the sediments are still expected to affect the nature of the plate interface. The size of petit-spot clusters in areas A and C roughly corresponds to the size of the rupture zones of M7–M8 interplate earthquakes here (Yamanaka and Kikuchi, 2004), implying the possibility that some M7–M8 interplate earthquakes may be associated with the subduction of petit-spot–altered sediments. For further observational insights, we need to investigate the nature of the subducting plate boundary in greater spatial detail. We suggest that the mechanical and alteration effects of post-spreading magmatism on the incoming plate could be a major co-factor that shapes the seismic nature of the megathrust seismic zone.

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REFERENCES CITED

Buchs, D.M., Pilet, S., Cosca, M., Flores, K.E., Bandini, A.N., and Baumgartner, P.O., 2013, Low-volume intraplate volcanism in the Early/Middle Jurassic Pacific basin documented by accreted sequences in Costa Rica: Geochemistry Geophysics Geosystems, v. 14, p. 1552–1568, https://doi.org/10.1002/ggge.20084.

Chester, F.M., et al., 2013, Structure and composition of the plate-boundary slip zone for the 2011 Tohoku-Oki earthquake: Science, v. 342, p. 1208–1211, https://doi.org/10.1126/science.1243719.

Divins, D.L., 2003, Total sediment thickness of the world's oceans and marginal seas (version 1): Boulder, Colorado, National Oceanic and Atmospheric Administration National Geophysical Data Center, https://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html.

Fujie, G., Kodaira, S., Yamashita, M., Sato, T., Takahashi, T., and Takahashi, N., 2013, Systematic changes in the incoming plate structure at the Kuril trench: Geophysical Research Letters, v. 40, p. 88–93, https://doi.org/10.1029/2012GL054340.

Fujie, G., Kodaira, S., Sato, T., and Takahashi, T., 2016, Along-trench variations in the seismic structure of the incoming Pacific plate at the outer rise of the northern Japan Trench: Geophysical Research Letters, v. 43, p. 666–673, https://doi.org/10.1002/2015GL067363.

Fujie, G., Kodaira, S., Kaiho, Y., Yamamoto, Y., Takahashi, T., Miura, S., and Yamada, T., 2018, Controlling factor of incoming plate hydration at the north-western Pacific margin: Nature Communications, v. 9, 3844, https://doi.org/10.1038/s41467-018-06320-z.

Grevemeyer, I., Ranero, C.R., and Ivandic, M., 2018, Structure of oceanic crust and serpentinization at subduction trenches: Geosphere, v. 14, p. 395–418, https://doi.org/10.1130/GES01537.1.

Hirano, N., et al., 2006, Volcanism in response to plate flexure: Science, v. 313, p. 1426–1428, https://doi.org/10.1126/science.1128235.

Ide, S., Baltay, A., and Beroza, G.C., 2011, Shallow dynamic overshoot and energetic deep rupture in the 2011 M_w 9.0 Tohoku-Oki earthquake: Science, v. 332, p. 1426–1429, https://doi.org/10.1126/science.1207020.

Iinuma, T., et al., 2012, Coseismic slip distribution of the 2011 off the Pacific coast of Tohoku earthquake (M9.0) refined by means of seafloor geodetic data: Journal of Geophysical Research, v. 117, p. 634–648, https://doi.org/10.1029/2012JB009186.

Kameda, J., Shimizu, M., Ujiie, K., Hirose, T., Ikari, M., Mori, J., Oohashi, K., and Kimura, G., 2015, Pelagic smectite as an important factor in tsunamigenic slip along the Japan Trench: Geology, v. 43, p. 155–158, https://doi.org/10.1130/G35948.1.

Kodaira, S., No, T., Nakamura, Y., Fujiwara, T., Kaiho, Y., Miura, S., Takahashi, N., Kaneda, Y., and Taira, A., 2012, Coseismic fault rupture at the trench axis during the 2011 Tohoku-oki earthquake: Nature Geoscience, v. 5, p. 646–650, https://doi.org/10.1038/ngeo1547.

Kodaira, S., Fujie, G., Yamashita, M., Sato, T., Takahashi, T., and Takahashi, N., 2014, Seismological evidence of mantle flow driving plate motions at a palaeo-spreading centre: Nature Geoscience, v. 7, p. 371–375, https://doi.org/10.1038/ngeo2121.

Lay, T., 2018, A review of the rupture characteristics of the 2011 Tohoku-oki Mw 9.1 earthquake: Tectonophysics, v. 733, p. 4–36, https://doi.org/10.1016/j.tecto.2017.09.022.

Machida, S., Hirano, N., Sumino, H., Hirata, T., Yoneda, S., and Kato, Y., 2015, Petit-spot geology reveals melts in upper-most asthenosphere dragged by lithosphere: Earth and Planetary Science Letters, v. 426, p. 267–279, https://doi.org/10.1016/j.epsl.2015.06.018.

Moore, J.C., Plank, T.A., Chester, F.M., Polissar, P.J., and Savage, H.M., 2015, Sediment provenance and controls on slip propagation: Lessons learned from the 2011 Tohoku and other great earthquakes of the subducting northwest Pacific plate: Geosphere, v. 11, p. 533–541, https://doi.org/10.1130/GES01099.1.

Nakamura, Y., Kodaira, S., Miura, S., Regalla, C., and Takahashi, N., 2013, High-resolution seismic imaging in the Japan Trench axis area off Miyagi, northeastern Japan: Geophysical Research Letters, v. 40, p. 1713–1718, https://doi.org/10.1002/grl.50364.

Ohira, A., Kodaira, S., Fujie, G., No, T., Nakamura, Y., Kaiho, Y., and Miura, S., 2018, Seismic structure of the oceanic crust around petit-spot volcanoes in the outer-rise region of the Japan Trench: Geophysical Research Letters, v. 45, p. 11,123–11,129, https://doi.org/10.1029/2018GL080305.

Peacock, S.M., and Wang, K., 1999, Seismic consequences of warm versus cool subduction metamorphism: Examples from southwest and northeast Japan: Science, v. 286, p. 937–939, https://doi.org/10.1126/science.286.5441.937.

Pytte, A.M., and Reynolds, R.C., 1989, The thermal transformation of smectite to illite, *in* Naeser, N.D., and McCulloh, T.H., eds., Thermal History of Sedimentary Basins: Methods and Case Histories: New York, Springer, p. 133–140, https://doi.org/10.1007/978-1-4612-3492-0_8.

Ruff, L.J., 1989, Do trench sediments affect great earthquake occurrence in subduction zones?: Pure and Applied Geophysics, v. 129, p. 263–282, https://doi.org/10.1007/BF00874629.

Saffer, D.M., and Marone, C., 2003, Comparison of smectite- and illite-rich gouge frictional properties: Application to the updip limit of the seismogenic zone along subduction megathrusts: Earth and Planetary Science Letters, v. 215, p. 219–235, https://doi.org/10.1016/S0012-821X(03)00424-2.

Shillington, D.J., Bécel, A., Nedimović, M.R., Kuehn, H., Webb, S.C., Abers, G.A., Keranen, K.M., Li, J., Delescluse, M., and Mattei-Salicrup, G.A., 2015, Link between plate fabric, hydration and subduction zone seismicity in Alaska: Nature Geoscience, v. 8, p. 961–964, https://doi.org/10.1038/ngeo2586.

Shipboard Scientific Party, 1980, Site 436: Japan Trench outer rise, Leg 56, *in* Scientific Party, Initial Reports of the Deep Sea Drilling Project, Volumes 56 and 57, Part 1: Washington, D.C., U.S. Government Printing Office, p. 300–446, https://doi.org/10.2973/dsdp.proc.5657.107.1980.

Ujiie, K., et al., 2013, Low coseismic shear stress on the Tohoku-Oki megathrust determined from laboratory experiments: Science, v. 342, p. 1211–1214, https://doi.org/10.1126/science.1243485.

Van Avendonk, H.J.A., Holbrook, W.S., Lizarralde, D., and Denyer, P., 2011, Structure and serpentinization of the subducting Cocos plate offshore Nicaragua and Costa Rica: Geochemistry Geophysics Geosystems, v. 12, Q06009, https://doi.org/10.1029/2011GC003592.

Vinnik, L.P., 1977, Detection of waves converted from P to SV in the mantle: Physics of the Earth and Planetary Interiors, v. 15, p. 39–45, https://doi.org/10.1016/0031-9201(77)90008-5.

Wang, K., and Bilek, S.L., 2014, Invited review paper: Fault creep caused by subduction of rough seafloor relief: Tectonophysics, v. 610, p. 1–24, https://doi.org/10.1016/j.tecto.2013.11.024.

Yamanaka, Y., and Kikuchi, M., 2004, Asperity map along the subduction zone in northeastern Japan inferred from regional seismic data: Journal of Geophysical Research, v. 109, B07307, https://doi.org/10.1029/2003JB002683.

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