Sediment provenance and controls on slip propagation: Lessons learned from the 2011 Tohoku and other great earthquakes of the subducting northwest Pacific plate

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ABSTRACT

The ~50 m slip of the Tohoku earthquake occurred along a very fine grained red-brown smectitic clay horizon subducting in the Japan Trench. This clay, cored in the plate boundary fault at Integrated Ocean Drilling Program Expedition 345, Site C0019, correlates with similar pelagic clay recovered seaward of the trench at Deep Sea Drilling Project Sites 436 and 1149. Comparable clays occur throughout the northwest Pacific Basin. Backtracking of ocean drilling Sites 436, C0019, and 1149 indicates that they formed during the Early Cretaceous at the Kula-Pacific Ridge. These sites traveled northwestward through the equatorial zone, accumulating siliceous and calcareous oozes until ca. 100–85 Ma. Sites 436, C0019, and 1149 then entered the realm of pelagic clay deposition where they remained until ca. 15 Ma. From ca. 15 Ma to the present, Sites 436, C0019, and 1149 accumulated clays and silty clays with variable amounts of siliceous microfossils and volcanic ash, representing the transition from deep-sea conditions to a continental margin sedimentary environment. The predicted backtracked vertical sequence of sediments fits well with the cores at Sites 436, 1149, and C0019, after accounting for structural complications in the latter.

Pelagic clay occurs in numerous boreholes penetrating the relatively smooth ocean floor of the Pacific plate north and northeast of the Tohoku earthquake. Here the widespread pelagic clay apparently fosters tsunami and tsunamigenic earthquakes. Seamounts rising above the normal oceanic crust accumulated sequences of calcareous sediments as their crests remained above the calcite compensation depth for most of their history. A seafloor including pelagic clay and carbonate-covered seamounts occurs south and southeast of the southern extent of the Tohoku earthquake rupture zone. This area has no historic tsunami or tsunamigenic earthquakes along the Japan and Izu-Bonin Trenches with the possible exception of the poorly located Enpo earthquake of A.D. 1677. We believe that the seamounts incoming on the oceanic plate to the south and southeast of the Tohoku rupture zone interfere with long-distance propagation of slip in the pelagic clay, limiting earthquake magnitude, shallow slip, and tsunami generation.

INTRODUCTION

Earthquakes that produce tsunamis are typically categorized in two ways. (1) Tsunami earthquakes are those that cause tsunamis greater in amplitude than would be expected from their surface wave magnitude (M_s) (Kanamori, 1972). (2) Tsunamigenic earthquakes are those that generate tsunamis (Polet and Kanamori, 2009) that scale directly with earthquake size. Both tsunamigenic and tsunami earthquakes are characterized by substantial shallow slip.

The moment magnitude (M_w) 9.0 Tohoku tsunamigenic earthquake of 2011 produced a very large tsunami along the coast of northern Honshu, Japan. The devastating tsunami had wave heights and run-ups exceeding anything known along this coast for more than a millennium (Lay and Kanamori, 2011). The earthquake lifted the seafloor by as much as 5 m and displaced it laterally ~50 m, thus generating the observed tsunamis (Lay and Kanamori, 2011). Lateral displacement was largest along the seaward-most portion of the principal thrust surface near the axis of the Japan Trench (Fig. 1) (Kodaira et al., 2012). Subsequently, Integrated Ocean Drilling Program (IODP) Expedition 343 (Site C0019) penetrated this seaward portion of the plate boundary thrust where it was buried 821 m below the seafloor (Chester et al., 2013).

These drilling results and associated seismic reflection data indicate that the plate boundary thrust is located in brown scaly clay that is near the base of the sedimentary section incoming on the Pacific plate (Fig. 1).

Many scientific ocean drilling boreholes have penetrated the Pacific plate east of the Japan Trench near the latitude of the Tohoku earthquake (Fig. 2). In this paper we correlate the stratigraphic sequence from the borehole penetrating the Tohoku plate boundary thrust (IODP Site C0019) to scientific ocean drilling holes on the adjacent Pacific plate, and we investigate the origin of the pelagic clay that accommodates the plate boundary thrust of the Tohoku earthquake. We speculate on how the distribution of the brown pelagic clay, relative to coeval seamounts, influences propagation of slip during earthquakes.

CORRELATION BETWEEN IODP SITE C0019 AND DEEP SEA DRILLING PROJECT SITE 436

To understand the structural evolution and sedimentary diagenesis and/or metamorphism of sediments in subduction zones, it is critical to have a reference site that samples the undisturbed sediments on the incoming oceanic plate. Time restrictions precluded the drilling of a designated reference site during IODP Expedition 343. Because the incoming sedimentary sequence on the subducting Pacific plate is relatively uniform in the vicinity of IODP Site C0019, Deep Sea Drilling Project (DSDP) Site 436, closest to Site C0019, was used as a reference site (Fig. 2). The age of the igneous oceanic crust at Site C0019 is 131 Ma and at Site 436 is 124 Ma; both sites originated at the Kula-Pacific spreading center (GeoMapApp, 2014, http://www.geomapapp.org/). Site 436 is on the outer swell of the Pacific plate incoming to
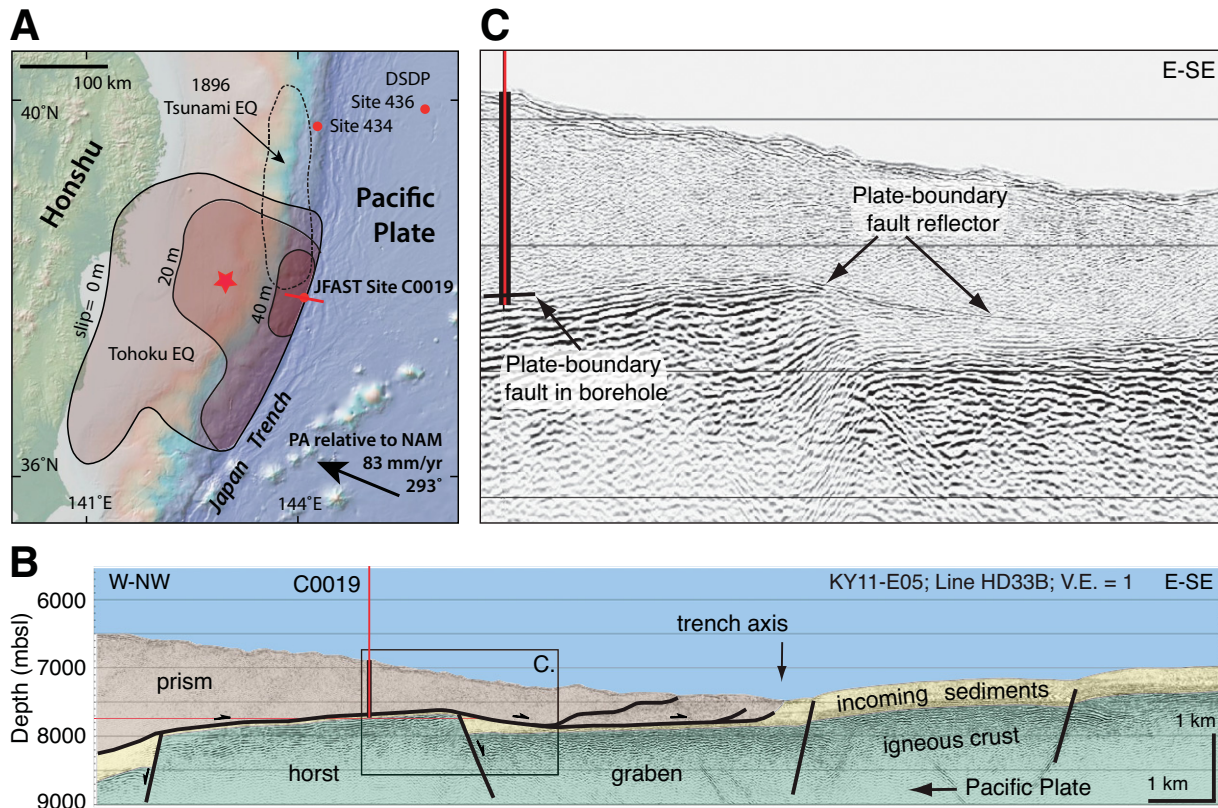
Figure 1. (A) Geologic setting of the 2011 Tohoku earthquake (Chester et al., 2013; Expedition 343/343T Scientists, 2013); star is epicenter. Convergence vector is for Pacific–North America (PA, NAM) motion (northern Japan is arguably part of the North American plate). EQ—earthquake; DSDP—Deep Sea Drilling Project. (B) Interpreted seismic line crossing Integrated Ocean Drilling Program Site C0019 showing the horst and graben structure of the incoming oceanic crust. Note that the plate boundary thrust rises from a graben and follows the top of the horst through Site C0019, and then drops back into the graben underlying the trench axis. V.E.—vertical exaggeration; mbsf—meters below seafloor; KY11-E05—R/V *KAIYO* cruise. (C) Detail of seismic line showing plate boundary thrust descending from horst into adjacent graben.

the Japan Trench (Fig. 1). Currently the Pacific plate converges with the continental margin at 83 mm/yr in the vicinity of Site C0019 (Fig. 1). As the Pacific plate flexes downward into the Japan Trench it is cut by normal faults on the seaward slope of the trench near both Sites 436 and C0019 (Fig. 1). The trench adjacent to Site 436 and C0019 shows little evidence of trench fill due to turbidite influx, but both regions probably receive a diffuse terrigenous hemipelagic cloud derived from Japan. Slumps from the trench slopes (Ogawa, 2011) could also contribute to the near-trench sediment influx.

Stratigraphy at Reference Site 436

At 398 m below seafloor (mbsf), Site 436 bottomed in Cretaceous chert older than 94 Ma (Fig. 3) (Doyle and Riedel, 1980). The chert sequence is overlain by brown pelagic clay 19 m thick. The age of the pelagic clay is estimated to range from Eocene to early Miocene based on fish teeth (Doyle and Riedel, 1980). No other

fossils were recovered from the clay, presumably because it accumulated in a deep, chemically corrosive oceanic environment. The clay apparently disconformably overlies the Cretaceous cherts, and accumulated at a very low rate of ~1 mm/10³ yr (uncompacted to surface porosity). From 360 mbsf to the water bottom, the pelagic clay is overlain by several units of mud and mudstone, and ooze with significant components of radiolarians, diatoms, and vitric debris.

Relationship of Sites 436 and C0019

Site C0019 has a stratigraphic progression similar to that of Site 436 (Fig. 3). Both holes bottom in Cretaceous chert overlain by redbrown clay in their basal sections. Both sites include a Miocene to Holocene sequence of mud and clay with abundant siliceous fossils and volcanic ash. A comparison of total sediment thickness at Sites 436 and C0019 indicates that C0019 is twice as thick, due to folding and thrust faulting, as indicated by age reversals

(Fig. 3). Recent detailed chemostratigraphic studies (H. Rabinowitz, 2014, personal commun.) and clay mineral analyses (Kameda et al., 2015) indicate that the scaly clay of Site C0019 correlates with the pelagic clay at Site 436. The thinner clay interval at Site C0019 relative to 436 may be due to unrecovered section during coring, which could boost the potential thickness to 5 m, or be due to shearing along the plate boundary fault zone. At Site C0019, the section below the scaly clay consists of mudstone and claystone of middle to late Miocene age that are out of stratigraphic sequence with respect to Site 436. Their location can be explained by normal faulting associated with the horst and graben structure of the outer rise followed by thrust faulting along the plate boundary thrust.

Experiments on the C0019 scaly clay and clays from Site 436 indicate that both are very weak with a coefficient of friction <0.1–0.2 over a range of slip velocities (Ujiie et al., 2013; M. Sawai et al., 2014). These sediments also show
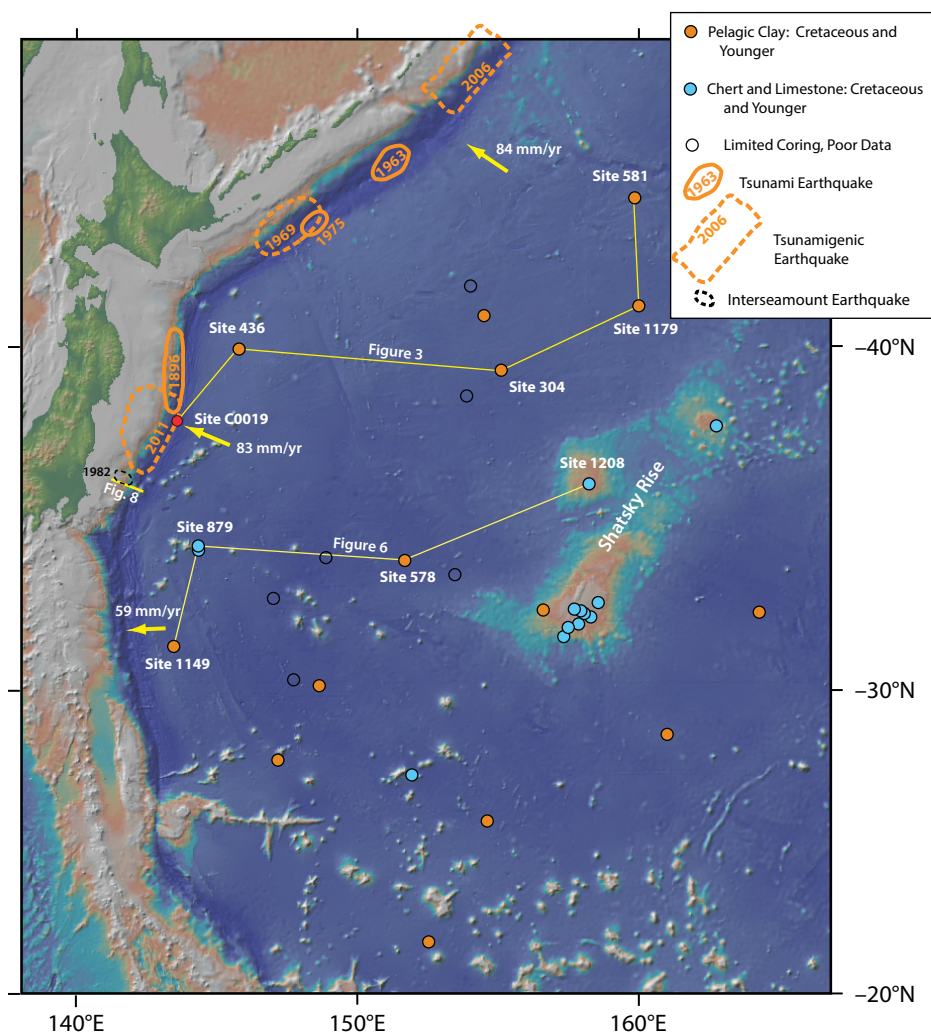
Figure 2. Northwest Pacific DSDP (Deep Sea Drilling Project), ODP (Ocean Drilling Program), and IODP (Integrated Ocean Drilling Program) holes (sites identified in Fig. 3 caption) with locations and dates of tsunami and tsunamigenic earthquakes (Fukao, 1979; Schwartz et al., 1989; Lay et al., 2009; Polet and Kanamori, 2009; Chester et al., 2013). An example of a small interseamount earthquake is shown just south of the 2011 Tohoku earthquake (Mochizuki, et al., 2008). The epicenter of this small earthquake is at the east-southeast extent of the rupture zone. In this figure, the ocean drilling boreholes are classified as those that show sections of pelagic clay sandwiched between chert-bearing Cretaceous rocks covered by muddy sediments containing varying amounts of radiolarians, diatoms, and volcaniclastic and terrigenous materials (in orange), and those with no significant intervals of pelagic clay but sections of chert, limestone, and locally Miocene and younger mudstone containing radiolarians, diatoms, and volcanic and terrigenous materials (in blue). Base map is from Ryan et al. (2009) and site locations and basic stratigraphic information are from GeoMapApp (http://www.geomapapp.org). For detailed stratigraphic information at drill sites from relevant DSDP, ODP, and IODP site reports, see Shipboard Scientific Party (1975, 1980, 1985a, 1985b, 1993, 2001, 2002) and Expedition 343/343T Scientists (2013).

very low fracture energy during slip weakening (M. Sawai et al., 2014). Overall the brown clays comprise an ideal surface for extensive fault slip.

The correlation between Sites C0019 and 436 is complicated by structure, but robustly justified by chronology, lithology, and overall stratigraphic sequence. Site 436 provides a well-characterized reference site that can be compared to numerous ocean drilling sites in the adjacent NW Pacific Ocean.

ORIGIN OF THE PELAGIC CLAY OF THE PLATE BOUNDARY THRUST IN THE NORTHWEST PACIFIC BASIN

The plate boundary thrust at Site C0019 is sited in a smectite-rich pelagic clay layer that fosters large amounts of slip (Chester et al., 2013; Fulton et al., 2013; Ujiie et al., 2013; M. Sawai et al., 2014; Kameda et al., 2015). Because of the apparent link to large tsunamis, it behooves us to investigate the origin of the special mineralogical and physical properties of this pelagic clay.

To better understand the genesis and distribution of the pelagic clay of the plate boundary thrust, we have examined drill sites on oceanic crust from the Japan, Kurile, and Izu-Bonin Trenches to ~165°E (Fig. 2). Of these sites, 55% preserve a brown pelagic clay layer; the remainder show carbonate, siliceous, volcaniclastic deposits, or a hiatus through the interval where the pelagic clay typically occurs (Late Cretaceous into Neogene). Ocean Drilling Program (ODP) Site 801, DSDP Site 307, and DSDP Site 567 at the southeastern portion of this area are still accumulating pelagic clay today because they are in deep water and starved of terrigenous, siliceous, or volcanic input. The sites lacking pelagic clays are on seamounts or other submarine highs where carbonate and siliceous sediments can accumulate above the calcite compensation depth (CCD), currently at ~4.3 km (Pälike et al., 2012).

FORMATION OF PELAGIC CLAY INTERVALS BY NORTHWESTWARD OCEANIC PLATE MOTION: A TECTONIC APPLICATION OF WALTHER'S LAW

The principle that facies in conformable vertical successions of strata represent once laterally adjacent environments is known as Walther's law (e.g., Prothero and Schwab, 2013). To understand the origin of the pelagic clay deposits at Sites C0019, 436, and 1149, we backtracked these sites from their current location to their positions in the Early Cretaceous. We used the most recent estimate of absolute Pacific plate motion in a reference frame that accounts for the motion of hotspots (Doubrovine et al., 2012). The backtracking motion is shown on the background of simplified modern Pacific Ocean geography (Fig. 4); to focus on the accumulation of sediments in the deeper portion of the ocean, we have left
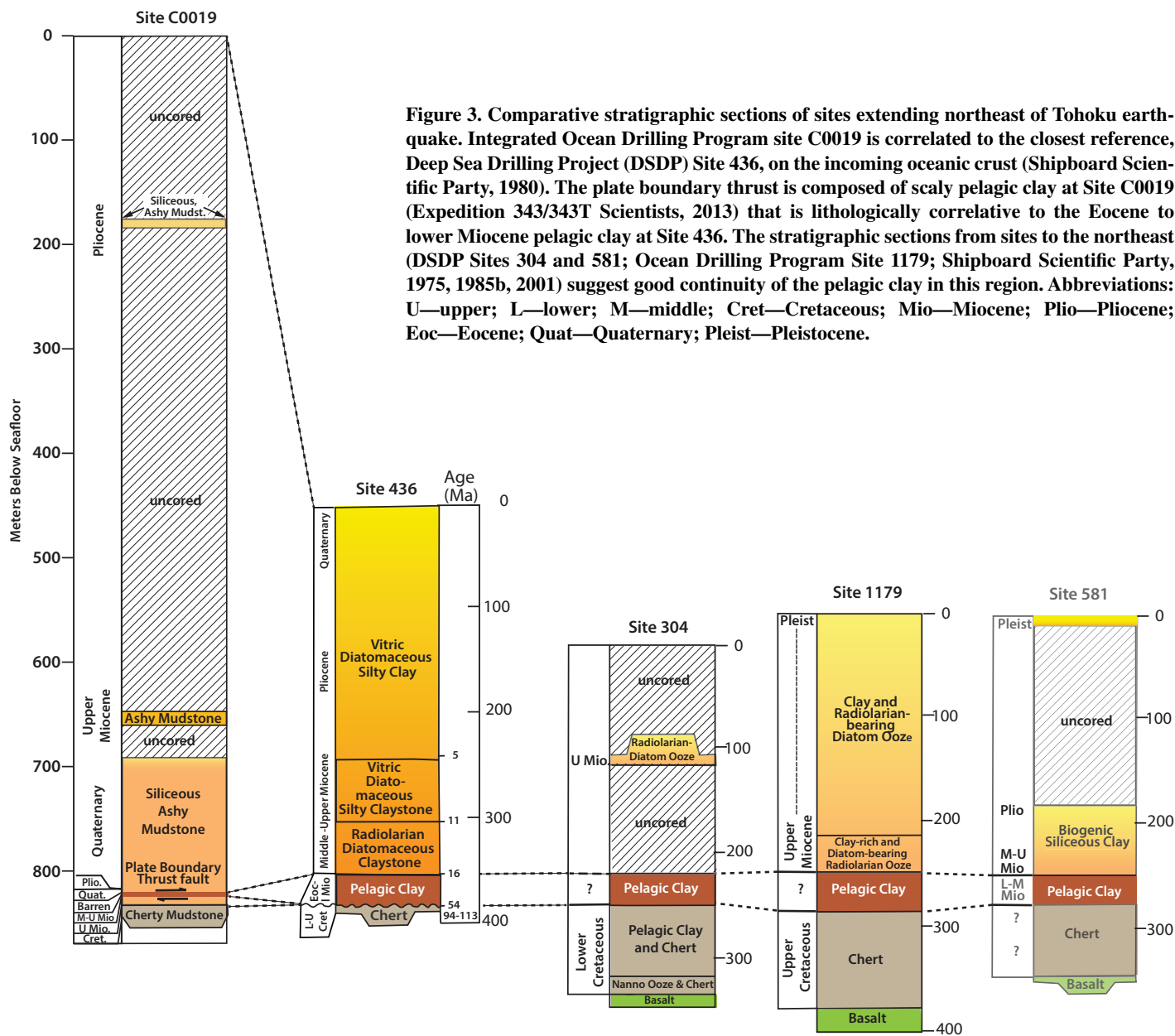
Figure 3. Comparative stratigraphic sections of sites extending northeast of Tohoku earthquake. Integrated Ocean Drilling Program site C0019 is correlated to the closest reference, Deep Sea Drilling Project (DSDP) Site 436, on the incoming oceanic crust (Shipboard Scientific Party, 1980). The plate boundary thrust is composed of scaly pelagic clay at Site C0019 (Expedition 343/343T Scientists, 2013) that is lithologically correlative to the Eocene to lower Miocene pelagic clay at Site 436. The stratigraphic sections from sites to the northeast (DSDP Sites 304 and 581; Ocean Drilling Program Site 1179; Shipboard Scientific Party, 1975, 1985b, 2001) suggest good continuity of the pelagic clay in this region. Abbreviations: U—upper; L—lower; M—middle; Cret—Cretaceous; Mio—Miocene; Plio—Pliocene; Eoc—Eocene; Quat—Quaternary; Pleist—Pleistocene.

oceanic islands, seamounts, and plateaus off this map.

During the early history of the backtracked sites, the Pacific Ocean would have been wider. The atmospheric and oceanic processes controlling biogenic production of sediment and sediment transport are strongly influenced by latitude and the position of continental margins. Thus, an earlier, wider Pacific ocean would probably have had sedimentation patterns similar to the modern distribution of sediments, albeit with some east-west lateral extension of the equatorial biogenic and pelagic clay deposits. The modern sediment distribution is wide

enough to contain the paths of the backtracked sites, and we have used this distribution to predict the vertical sedimentary sequences that would have developed (Fig. 4).

Translating the drill sites forward through time from the Cretaceous illustrates how the stratigraphic sequences accumulate and substantiates use of the modern sediment patterns to approximate late Mesozoic and Cenozoic sediment distribution. The temporally forward motion of the backtracked sites shows the following.

1. The sites began life in the equatorial upwelling zone where they would have accumulated siliceous and calcareous sediments for ~30 m.y.;

these sediments were ultimately transformed to chert. The coring recovered mostly cherty nodules, apparently washing out softer sediments, probably largely composed of siliceous and calcareous microfossil ooze. From their inception at 2–3 km below sea level at the Kula-Pacific Ridge, the sites would have gradually subsided as the Pacific plate cooled (Parsons and Sclater, 1977) (Fig. 5A).

2. The sites entered the zone of pelagic clay deposition ca. 100–85 Ma. Pelagic clay deposition continued until ca. 20 Ma.

3. After ca. 15 Ma, deposition transitioned to sediments with substantial amounts of sili-

Figure 4. Map of backtracked Integrated Ocean Drilling Program (IODP) Site C0019, Deep Sea Drilling Project Site 436, and Ocean Drilling Program 1149 in 10 m.y. increments. Backtracking uses poles of absolute plate motions that account for movement of hotspots (Doubrovine et al., 2012). Because poles of rotation were unavailable for earlier than 120 Ma, the site locations for 130 Ma and place of origin cannot be specified. See question mark to right of 120 Ma backtrack location. However, paleomagnetic data from Site 1149 (Shipboard Scientific Party, 2000) suggest that it, and probably Sites 436 and C0019, originated south of the equator. Backtracking overlies a map of modern North Pacific sediment distribution that shows deep-water deposits and excludes those on seamounts and oceanic islands (Horn et al., 1970; Davies and Gorseline, 1976). Although this sediment distribution is that of the Holocene, we believe its earlier history would have had similar sediment belts that were perhaps laterally more extensive because of the wider Pacific Ocean. Note that Sites C0019 and 436 are moving through the pelagic clay area from ca. 100 Ma (middle Cretaceous) to ca. 15 Ma (Miocene). Site 1149 has a similar path through the depositional environment of the pelagic brown clay.
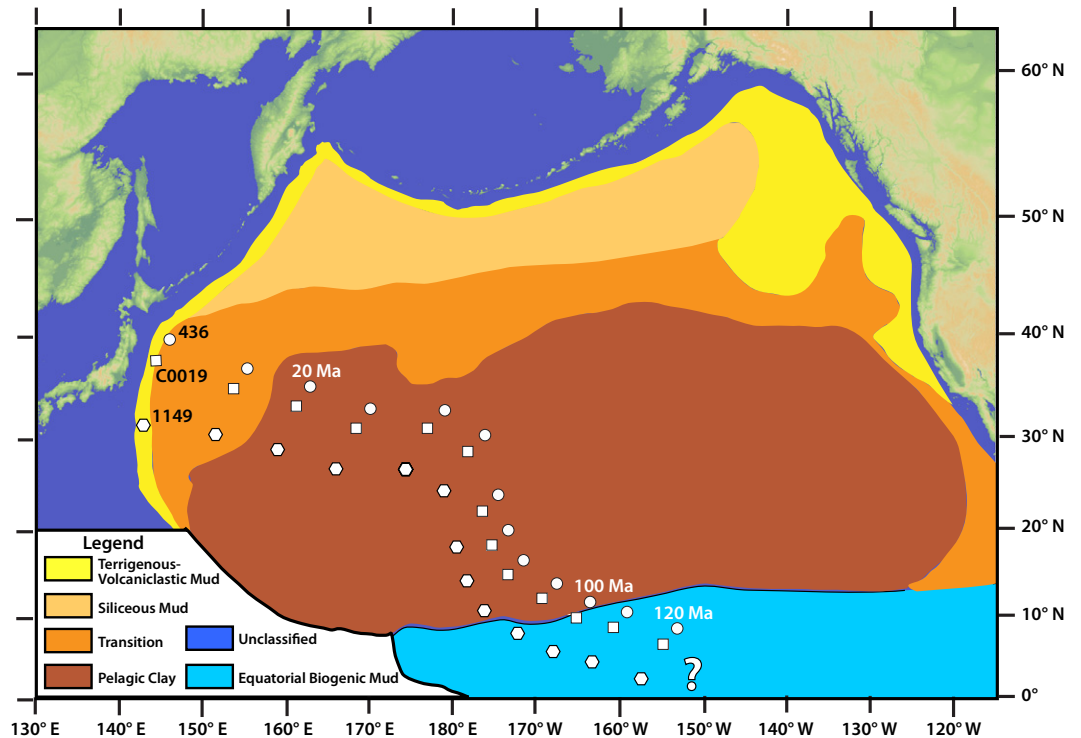
ceous microfossils and finally to sediments with increasing terrigenous and volcaniclastic influx from Japan (Fig. 5A).

The predicted lithology and age transitions at Site 436 are in good agreement with the cored sedimentary section (Fig. 5A); it is therefore reasonable to ascribe the pelagic clay layers in the other sites identified in Figure 3 as due to lateral northwestward movement through the depositional realm of the pelagic clay.

Figure 5A excludes the nature of sediments that accumulated on high-relief areas of the oceanic plate such as oceanic plateaus and seamounts. Figure 5B illustrates how a seamount originating within ~1 km of the sea surface would spend most of its history above the carbonate compensation depth (Van Andel, 1975; Pälike et al., 2012). Sites where this Late Cretaceous to Neogene pelagic clay layer does not exist were originally seamounts or other oceanic highs that did not submerge below the CCD for sufficient time to accumulate the pelagic clay (Fig. 5B). Figure 6 shows how the seamount sites, dominated by carbonate sediments (e.g., Sites 879 and 1208), occur interspersed with sites with pelagic clay layers (e.g., Site 1149) on the Pacific plate in the area south and southeast of the Tohoku earthquake rupture zone (see Fig. 2 for site locations).

DISTRIBUTION OF PELAGIC CLAY AND SEAMOUNTS RELATIVE TO EARTHQUAKES WITH LARGE SHALLOW SLIP

Earthquakes with large thrust displacement at shallow depths beneath the seafloor tend to produce tsunamis larger than expected from their moment magnitude (Kanamori, 1986; Polet and Kanamori, 2009). Series of earthquakes extending from the Tohoku earthquake rupture zone to the northeast along the Japan and Kurile Trenches have produced substantial tsunamis (Fig. 2). The drill sites offshore of the earthquakes consistently show a layer of pelagic clay tens of meters thick that correlates with the interval that became the principal thrust fault surface for the Tohoku earthquake (Site C0019) (Figs. 2 and 3). The pelagic clay layers are succeeded upsection by several hundred meters of mudstone mixed with various amounts of radiolarians, diatoms, and volcanic ash. This area is characterized by a relatively smooth seafloor offshore of the regions producing the tsunami earthquakes (Fig. 2).

South and southeast of the Tohoku rupture zone, along the Japan and Izu-Bonin Trenches, there have been no historic, instrumentally

recorded earthquakes that produced notable tsunamis (Polet and Kanamori, 2009). The relatively low seismicity of the Izu-Bonin arc has been attributed to low compressional stress across the subduction zone (Uyeda and Kanamori, 1979). The seafloor east of the southern portion of the Japan Trench and the Izu-Bonin Trench is characterized by concentrations of seamounts and other small plateaus (Fig. 2). These features are capped by carbonate ooze, limestone, and volcanic and limestone breccias, with no significant accumulations of pelagic clay (Fig. 5B). However, boreholes in the basins between seamounts and small plateaus show pelagic clay layers (Fig. 6; Sites 578 and 1149) similar to sites on the Pacific plate northeast of the Tohoku rupture zone (Fig. 3).

We quantified the nature of the Pacific plate seafloor described above as smooth or rough using a seamount census from altimetry-derived gravity data (Kim and Wessel, 2011), by counting the number of seamounts >1 km high above the adjacent seafloor along swaths extending seaward from the trench and laterally along the trench. These swaths extend 500 km seaward from the Japan Trench and related trenches, and along its trend in two directions, north and south. The swaths are 1800 km northward and 2100 km southward from lat 37.5°N. Within these,
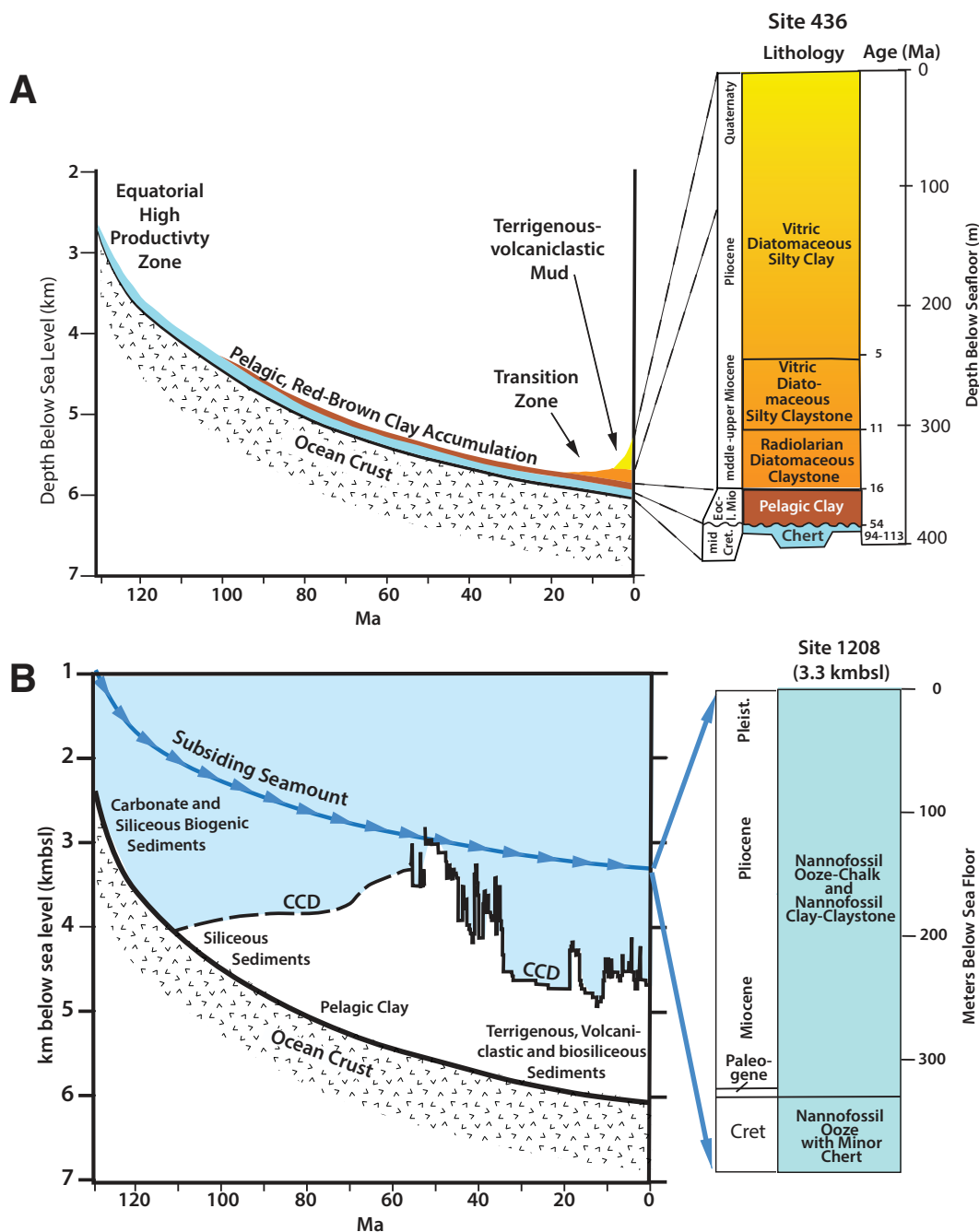
Figure 5. (A) Vertical sedimentary sequence accumulated at Deep Sea Drilling Project Site 436 and probably at Integrated Ocean Drilling Program Site C0019 prior to deformation. The sequence is due to lateral transport from an equatorial zone of high productivity through an environment of slow distal deposition of pelagic clays and transition to continental margin sedimentation. Continental margin sedimentation is characterized by both coarser grain sizes and abundant siliceous fossils produced by active upwelling. Depth and age of oceanic crust are shown from the original locations of of Sites 436, C0019, and 1149 ca. 124, 132, and 133 Ma, respectively. The age versus depth relationship for North Pacific oceanic crust is from Parsons and Sclater (1977); the lithology and ages of Site 436 are from Shipboard Scientific Party (1980). Abbreviations as in Figure 3. **(B)** Diagram shows depth of calcite compensation depth (CCD) (Van Andel, 1975; Pälike et al., 2012) and depth of subsiding oceanic crust for the North Pacific Ocean (Parsons and Sclater, 1977). The estimated subsidence curve for a seamount now at 3.3 km below sea level indicates that it would always have been above the CCD, excepting perhaps ca. 50–55 Ma. Sediments that would accumulate below the CCD are shown along the oceanic crust subsidence curve. Minor amounts of these dissolution-resistant sediments accumulate on the seamount but are diluted by the heavy carbonate influx. A number of seamounts show unconformities or condensed sections in the Paleogene because of the slow accumulation of sediments at these sites as they pass through the pelagic clay depositional zone at a depth close to the CCD at 50–55 Ma. (e.g., Shipboard Scientific Party, 2002).
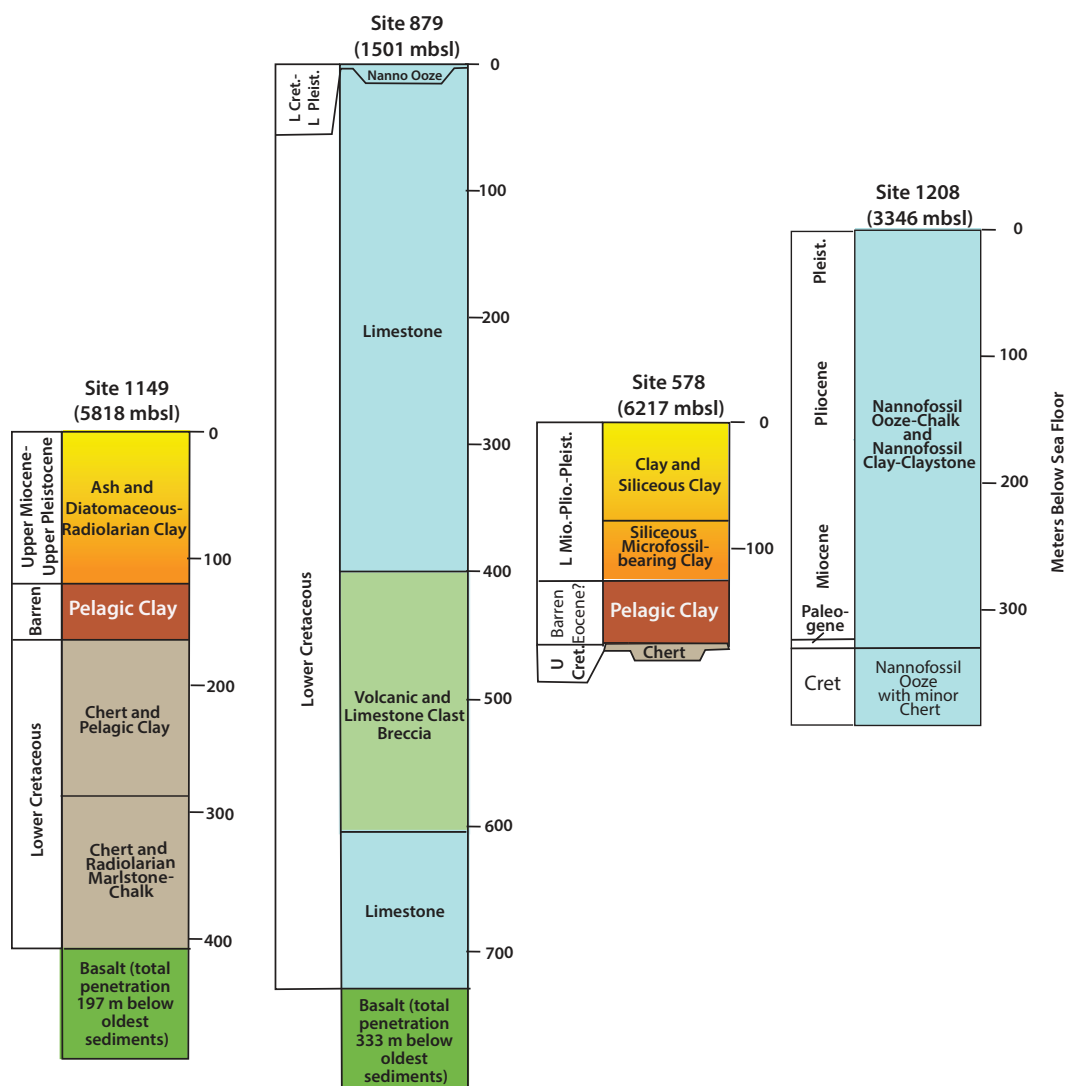
Figure 6. Lithologic columns from drilling sites south and southeast of the Tohoku earthquake. Many seamounts in this area are shallow due both to initial volcanic construction and rapid carbonate sedimentation (mbsl—meters below sea level; other abbreviations as in Fig. 3). Ocean Drilling Program (ODP) Sites 879 and 1208 illustrate the carbonate highs (Shipboard Scientific Party, 1993, 2002). Between seamounts the oceanic sedimentation is similar to that farther north with well-developed pelagic clay sequences, as shown at Deep Sea Drilling Project Site 578 and ODP Site 1149 (Shipboard Scientific Party 1985a, 2000).

the frequency of seamounts north of 37.5°N (the approximate latitude of C00019) with an elevation >1 km is 1 seamount per 138 km of trench length to the north; the frequency south of 37.5°N is 1 seamount per 27 km of trench. Therefore the frequency of incoming seamounts along the trench is 5 times higher south of 37.5°N than to the north along the trench of the subducting Pacific plate. The seamount count will probably become more detailed as new satellite data become available and more direct measurements of seafloor bathymetry are collected. However, it is unlikely new data will affect the observed pattern.

DISCUSSION

The above observations indicate that incoming sediments containing a uniform layer of pelagic clay covered by relatively thin overburden, and largely uninterrupted by carbonate-capped seamounts, correlate with subduction boundary segments producing tsunami and tsunamigenic earthquakes. The pelagic clay forms the plate boundary fault of the Tohoku earthquake (Figs. 3 and 7), and it is reasonable to assume that this weak layer would likewise facilitate the subduction zone to the northeast, providing that the overburden is thin, can be easily deformed, and can displace a significant amount of overlying seawater (e.g., Gulick et al., 2011). This incoming stratigraphy and relatively smooth seafloor apparently correlate with a high concentration of tsunamis in this region (Fig. 2). Conversely, where the pelagic clay layers are interrupted by carbonate capped seamounts (Figs. 6 and 8), large tsunamis are not observed (Fig. 2).

Recent observational evidence suggests that seamounts subduct largely aseismically, producing numerous small earthquakes (Wang and Bilek, 2011, 2014). Areas adjacent to the seamounts release strain on the subduction thrust with repeating earthquakes of moderate size but lacking large shallow slip (Mochizuki et al., 2008). Just south of the Tohoku earthquake rupture zone, a seamount chain enters the trench (Fig. 2). A seamount in this chain, buried ~7 km below the seafloor, apparently was associated with an Mw 7 earthquake (Mochizuki et al., 2008). The same locality has been subject to similar earthquakes repeating about every 20 yr. We speculate that this process of interseismic deformation of seamounts by tremor or creep (Wang and Bilek, 2014) prevents the patchy pelagic clay deposits between seamounts from unleashing an extensive shallow slip earthquake that would produce a large tsunami (Fig. 8). Following the Wang and Bilek (2014) perspective, we believe that the irregular geometry and unique physical properties of seamounts hinder
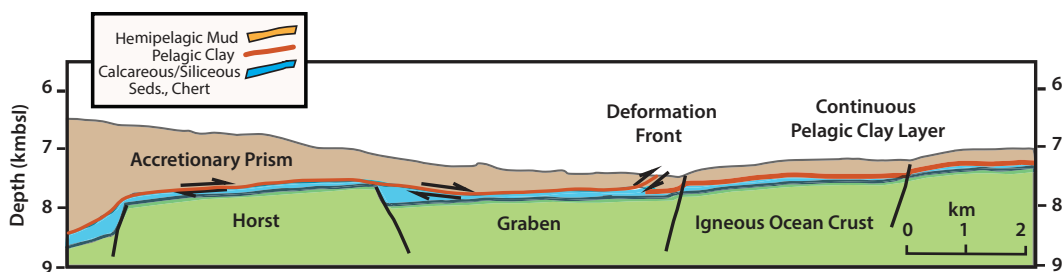
Figure 7. Tohoku earthquake shallow slip model showing localization of plate boundary faulting along pelagic clay as observed in the tsunamigenic Tohoku earthquake. Uninterrupted slip is fostered by the continuity of the weak pelagic clay layer and minimal overburden, in spite of the horsts and grabens on the incoming oceanic crust (kmbsl—kilometers below sea level; Seds.—sediments).
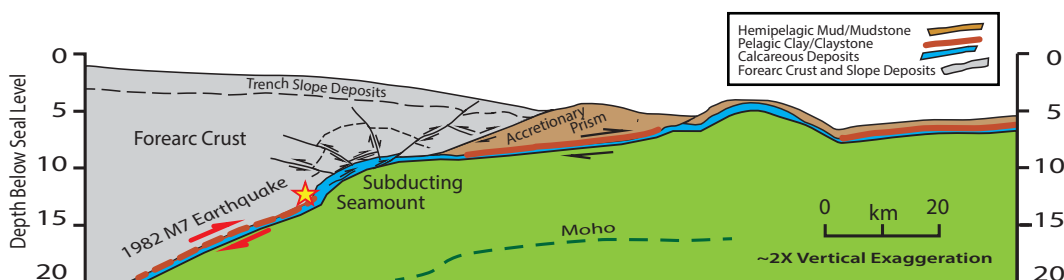
Figure 8. Seamount-induced compartmentalized earthquake failure: cross section is subduction of oceanic crust with carbonate-covered seamounts interspersed between regions of pelagic clay (Mochizuki et al., 2008). The 1982 earthquake initiated at the edge (star) of the subducting seamount. The earthquake propagated downdip away from the seamount and did not produce a significant tsunami. Here, similar ~M7 earthquakes repeat about every 20 yr (Mochizuki et al., 2008). The lack of ~M7 earthquakes centered on the seamount suggests that its weak interplate coupling is associated with distributed deformation of the seamount and overlying forearc crust during the interseismic period (Wang and Bilek, 2014). The geometry of the upper plate rock units is generalized from Tsuru et al. (2002) and von Huene et al. (1994).

propagation of earthquake slip; the seamounts compartmentalize the fault surface and limit the extent of earthquake slip and the production of large tsunamis.

The Enpo earthquake of 1677 was shown to have extended directly south from the southern boundary of the Tohoku rupture zone along the Japan Trench (e.g., Y. Sawai et al., 2014). Although the occurrence of this earthquake is undisputed, its location is controversial due to lack of regional tsunami run-up observations. Rather than being due to Pacific plate subduction, this earthquake may have occurred due to the subduction of the Philippine Sea plate beneath the Japanese continental margin, along the Sagami Trough (Y. Ogawa, 2014, personal commun.). Because of the controversy regarding its location, we excluded the Enpo earthquake from our compilation (Fig. 2).

Pelagic clays are widespread in deep central oceanic areas (Jenkyns, 1986) and are ultimately swept into subduction zones. Because of the ubiquity of weak smectitic pelagic clay, there should be a global correlation of these clays with the subduction zones, smooth seafloor, and the production of tsunamis due to enhanced shallow slip.

CONCLUSIONS

1. The scaly clay of the plate boundary thrust penetrated during IODP Expedition 343 at Site C0019 correlates to a brown, very fine grained, smectitic pelagic clay of Eocene to middle-late Miocene age at Site 436 on the outer rise of the incoming oceanic plate.

2. Backtracking of the locations of Sites C0019, 436, and 1149 to their initial positions of formation predicts that they would accumulate Cretaceous siliceous and calcareous sediments, Cretaceous to Miocene red-brown pelagic clay, and Miocene and younger clastic sediments with components of diatoms, radiolarians, and terrigenous and volcaniclastic deposits. This lithologic progression is observed at Site 436 and generally reproduced at many other sites offshore of northern Japan (Fig. 3).

3. Seamounts immediately east and southeast of Sites 436, C0019, and 1149 originated near the equator. Many of these highs in the oceanic crust have accumulated calcareous ooze and limestone from Cretaceous into the Neogene because they never subsided below the CCD (Figs. 5B and 6).

4. Northwest of the Tohoku earthquake rupture zone, sedimentary sequences incoming to the subduction zone are similar to those at Site 436; seamounts with extensive carbonate and biosiliceous sediments are rare. We hypothesize that the apparently extensive and continuous layer of pelagic clay with minimal overburden enabled shallow large-slip tsunami and tsunamigenic earthquakes along the northern Japan and Kurile subduction zones (Figs. 2 and 7).

5. The region south and southeast of the Tohoku rupture zone, along the Japan and Izu-Bonin Trenches, has not produced instrumentally recorded tsunamis or tsunamigenic earthquakes. We hypothesize that here the occurrence of seamounts with biogenic (calcareous and siliceous) sedimentary caps break the continuity of the pelagic clay layers, hinder throughgoing slip at shallow depths, and suppress tsunamis.

6. Pelagic clays are widespread in deep central oceanic areas (Jenkyns, 1986) and are ultimately swept into subduction zones. The ubiquity of weak smectitic pelagic clays should encourage a global correlation of these clays with subduction zones, smooth seafloor, and the production of tsunamis due to enhanced shallow slip.

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