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SEDIMENT PROVENANCE AND CONTROLS ON SLIP PROPAGATION: LESSONS LEARNED FROM THE 2011 TOHOKO AND OTHER EARTHQUAKES OF THE SUBDUCTING NW PACIFIC PLATE

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SEDIMENT PROVENANCE AND CONTROLS ON SLIP PROPAGATION: LESSONS LEARNED FROM THE 2011 TOHOKO AND OTHER EARTHQUAKES OF THE SUBDUCTING NW 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. This clay, cored in the plate boundary fault at IODP Site C0019, correlates with similar pelagic clay recovered seaward of the trench at DSDP Site 436. Correlative pelagic clays occur throughout the NW Pacific Basin. Backtracking of Sites C0019 and 436 indicates 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 about 100 Ma. Then, Sites C0019 and 436 entered the realm of pelagic clay deposition where they remained until about 15 Ma. After 15 Ma Sites C0019 and 436 accumulated clays, silty clays with variable amounts of siliceous microfossils and volcanic ash—representing the transition to a continental margin sedimentary environment. Overall the predicted vertical

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INTRODUCTION

The M_w 9.0 Tohoku earthquake of 2011 produced a very large tsunami along the coast of northern Honshu, Japan. The devastating tsunami had wave heights and run-ups exceeded 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 40 to 50 m 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 (Figure 1) (Kodaira et al., 2012). Subsequently an Integrated Ocean Drilling Program (IODP) penetrated this seaward portion of the plate-boundary thrust where it was buried 821 m below the sea floor (Chester et al., 2013). These drilling results and associated seismic refection data indicate that the plate boundary thrust is located in brown scaly clay that lies near the base of the sedimentary section incoming on the Pacific Plate (Figure 1).

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

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). Notable tsunamigenic earthquakes are those with large tsunamis that scale directly with earthquake size. Both tsunamigenic and tsunami earthquakes are characterized by substantial shallow slip that results in the tsunami. The tsunami generating slip is commonly relatively slow. The fault geometry is unspecified. The Tohoku earthquake was a tsunamigenic earthquake.

CORRELATION BETWEEN IODP SITE C0019 AND DSDP SITE 436

To understand the structural evolution and sedimentary diagenesis/metamorphism of sediments in subduction zones it is critical to have a reference site sampling the undisturbed sediments on the incoming oceanic plate. Time requirements for other cruise activities 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, DSDP Site 436 was deemed to be sufficiently similar for reference site comparisons. Site 436 is closest to Site C0019 of those drilling sites on the Pacific Plate (Figure 2). The age of the igneous oceanic crust at Site C0019 is 131 Ma and at Site 436 124 Ma: both sites originated at the Kula-Pacific spreading center (GeoMapApp, 2014). Site 436 lies on the outer swell of the Pacific Plate incoming to the Japan Trench (Figure 1). Currently the Pacific Plate converges with the continental margin at 83 mm/yr in the vicinity of Site C0019. As the Pacific Plate flexes downward into the Japan Trench it is cut by normal faults on the seaward slope of the trench both near Sites 436 and C0019 (Figure 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 Site 436*:** At 398 meters below seafloor (mbsf), Site 436 bottomed in Cretaceous chert greater than 94 my old (Figure 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 caustic oceanic environment. The clay apparently disconformably overlays the Cretaceous cherts, and the clay accumulated at a very low rate of about 1 mm/10^3 years (uncompacted to surface porosity). From 360 mbsf to the waterbottom, the pelagic clay is overlain by several units of mud-mudstone, and ooze with significant components of radiolarians, diatoms, and vitric debris.

Correlation to Site 436: Overall Site C0019 has a similar stratigraphic progression as Site 436. Both holes bottom in Cretaceous chert. Both sites include a very fine grained red-brown clay in its basal section. And both sites include a Miocene to Holocene mud and clay section with abundant siliceous fossils and volcanic ash. A comparison of total sediment thickness at Site 436 and C0019 indicates that C0019 is twice as thick, due to folding and thrust faulting as indicated by age reversals (Figure 3). A 1 m section of scaly brown clay in Site C0019 is interpreted as the plate-boundary fault zone and correlated to the pelagic clay section in Site 436 (Chester et al., 2013). 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. Recent detailed chemostratigraphic studies (owitz et al., 2013) and clay mineral analyses (J. Kameda, personal communication) suggest that the scaly clay of Site C0019 correlates with the pelagic clay at Site 436. At Site C0019, the section below the scaly clay consists of mudstone and claystone of middle to late Miocene age. The Miocene rocks lie on top of the Cretaceous porcellanite and chert. These Miocene rocks at Site C0019 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 less than 0.1 to 0.2 over a range of slip velocities (Ujiie et al., 2013; Sawai, Hirose, and Kameda, 2014). These sediments also show very low fracture energy during slip weakening (Sawai, Hirose, and Kameda, 2014). Overall the brown clays comprise an ideal surface for extensive fault slip.

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

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

The lithology of the plate boundary thrust at Site C0019 correlates to the pelagic clay layer at Site 436. This lithology is very weak and fosters large amounts of slip, at least, because it is very fine grained, and smectite-rich (Chester et al., 2013; Fulton et al., 2013; Kameda personal communication). The apparent linkage to large tsunamis 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 comprising the plate boundary thrust, we have examined drill sites east from the Japan and Izu Bonin Trenches to about 165^{o}E (Figure 2). Fifty-five percent of the sites preserve a brown pelagic clay layer with the remainder showing 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 south eastern portion of this area are still accumulating pelagic clay today because they are in deep water and starved of input of terrigenous or siliceous mud. The sites lacking pelagic clays are on seamounts or other submarine highs where carbonate and siliceous sediments can accumulate above the calcite compensation depth, currently at about 4.3 km.

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

The principle that facies that occur in conformable vertical successions of strata also occurred in 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 Site C0019, Site 436 and other localities in the NW Pacific, we backtracked Sites C0019 and Site 436 to their point of origin using 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 (Figure 4). To focus on the accumulation of sediments in the deeper portion of the ocean we have left oceanic islands, seamounts and plateaus off this map. We make stratigraphic comparisons from sediments accumulated during the predicted paths of plate motion to the sequence preserved at Site 436 as it is not disturbed by faulting unlike Site C0019. We believe the depositional history of Site C0019 was similar to that recorded by Site 436.

During the earlier history of Sites 436 and C0019, 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 was wide enough to contain the backtracked paths of Sites C0019 and 436, and we have used this distribution to predict the vertical sedimentary sequences that would have developed.

Translating the drill sites forward through time, reversing their backtracked paths, illustrates how the vertical 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:

1) Sites C0019 and 436 began life in the equatorial upwelling zone where they would have accumulated siliceous and calcareous sediments for about 30 Ma; these sediments were ultimately transformed to chert as recovered in the cores. The coring only recovered cherty nodules, apparently washing-out softer sediments, likely largely composed of siliceous and calcareous microfossil ooze. From their formation at the Kula-Pacific Ridge, Sites C0019 and 436 would have gradually subsided as the Pacific Plate cooled (Parsons and Sclater, 1977) (Figure 5A).

2) Sites C0019 and 436 entered the zone of pelagic clay deposition at about 100 Ma. Pelagic clay deposition continued until about 15-20 Ma.

3) After about 15 Ma, deposition transitioned to sediments with substantial amounts of siliceous microfossils and finally to sediments with increasing terrigenous and volcaniclastic influx from Japan (Figure 5A).

The predicted lithology and age transitions at Site 436 are in good agreement with the cored sedimentary section (Figure 5A). It is 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 accumulating on high areas of the oceanic plate such as oceanic plateaus and seamounts. Figure 5B illustrates how a seamount within km of the sea surface would spend most of its history above the carbonate compensation depth (Van Andel, 1975; Palike and et al., 2008). Sites where this late Cretaceous to Neogene pelagic clay layer doesn't exist were originally seamounts or other oceanic highs that did not submerge below the CCD for sufficient time to accumulate the pelagic clay (Figure 5B). Figure 6 shows how the seamount sites, dominated by carbonate sediments, occur interspersed with sites with pelagic clay layers, on the Pacific Plate, in the area south and southeast of the Tohoku earthquake rupture zone (Figure 6).

DISTRIBUTION OF PELAGIC CLAY AND SEAMOUNTS VERSUS 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). A series of earthquakes extending from the Tohoku earthquake rupture zone to the northeast along the Japan and Kurile Trenches have produced substantial tsunamis. 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) (Figures 2,3). The pelagic clay layers are succeeded up section by several hundred meters of mudstone mixed with various amounts of radiolarians, diatoms, and volcanic ashes. This area is characterized by a relatively smooth seafloor offshore of the regions producing the tsunami earthquakes (Figure 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 have produced notable tsunamis (Polet and Kanamori, 2009). The 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 seamounts and other small plateaus (Figure 2). The seamounts and small plateaus in oceanic basement are capped by carbonate ooze, limestone, and volcanic and limestone breccias, but show no significant accumulations of pelagic clay (Figure 5B). However boreholes in the basins between seamounts and small plateaus do show pelagic clay layers (Figure 6) similar to Sites on the Pacific Plate northeast of the Tohoku rupture zone (Figure 3).

We quantified the nature of the Pacific Plate seafloor described above as “smooth” and “rough” using a seamount census from altimetry-derived gravity data (Kim and Wessel, 2011). Accordingly, we counted the number of seamounts greater than 1 km high above the adjacent seafloor along a swaths extending seaward from the trench and laterally along the trench. These swaths extend 500 km seaward from the Japan Trench and along its trend in two directions, north and south. The swaths measure 1800 km northward from 37.5 ^{o} N and 2100 km southward from

37.5° N. In these swaths the frequency of seamounts with an elevation greater than 1 km is 1 seamount per 138 km of trench length to the north and 1 seamount per 27 km of trench length to the south. Therefore the frequency of incoming seamounts along the trench is 5 times higher to the south than to the north along the composite Japan and Izu-Bonin trench. The seamount count will probably become more detailed as new satellite data become available and more direct measurements of seafloor bathymetry are collected by marine scientists. However, it is unlikely to change the trends of fewer Pacific Plate seamounts subducting north and more seamounts subducting south of the Tohoku earthquake rupture zone.

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 plate boundary segments producing tsunami and tsunamigenic earthquakes. The pelagic clay forms the plate boundary fault of the Tohoku earthquake (Figure 7); it is reasonable to assume that this weak layer would also behave similarly along 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 accounts for the concentration of tsunamis in this region (Figure 2). Conversely where the pelagic clay layers are interrupted by carbonate capped seamounts (Figures 6,8), large tsunamis are not observed (Figure 2).

Recent observational evidence suggests seamounts subduct largely aseismically producing numerous small earthquakes (Wang and Bilek, 2011, 2014). Areas adjacent to the seamount 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, the Jogan seamount chain enters the trench (Figure 2). A seamount in this chain, buried about 7 km below the seafloor, apparently was associated with a Mw 7 earthquake (Mochizuki et al., 2008). The same locality has been subject to similar earthquakes repeating about every 20 years. We speculate that this process of inter-seismic deformation of seamounts by tremor or creep (Wang and Bilek, 2014) prevent the patchy pelagic clay deposits between seamounts from unleashing an extensive shallow slip earthquake that would produce a large tsunami (Figure 8). Following Wang and Bilek's perspective we believe the irregular geometry and differing sediment physical properties of seamounts are hindering the propagation of earthquake slip. Thus, the seamounts **compartmentalize** the fault surface and limit the extent of earthquake slip and the potential for production of large tsunamis.

Scientific presentations have shown the Enpo Earthquake of 1677 extending directly south from the southern boundary of the Tohoku rupture zone along the Japan Trench (e.g. Sawai, Tanagawa, 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 Philippine Sea Plate subduction beneath the Japanese continental margin, along the Sagami Trough (Yujiro Ogawa, personal communication). Because of the controversy in its location, we have excluded the Enpo Earthquake from our compilation (Figure 2).

Finally, 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 behooves us to attempt to 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 Exp. 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 Sites C0019 and 436 to their initial locations 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 (Figure 3).
3) Many seamounts immediately east and southeast of Sites C0019 and 436 also originated near the equator. Many of these highs in the oceanic crust have accumulated biogenic sediments from Cretaceous into the Neogene because they never subsided below the calcite compensation depth (Figures 5B, 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 the tsunami and tsunamigenic earthquakes along the Northern Japan and Kurile subduction zones (Figure 2, 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 sedimentary caps break the continuity of the pelagic clay layers, hinder through-going slip at shallow depths, and suppress tsunamis.

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FIGURE CAPTIONS

Figure 1. A. Geologic setting of the 2011 Tohoku earthquake (modified from Chester et al., 2013). Tohoku earthquake epicenter shown by star. Convergence vector is for Pacific-North America motion (Northern Japan is arguably part of the North American Plate). B. Interpreted seismic line crossing 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. C. Detail of seismic line showing plate boundary thrust descending from horst into adjacent graben.

Figure 2. Northwest Pacific DSDP, ODP, and IODP holes with locations of tsunami and tsunamigenic earthquakes (Fukao, 1979; Schwartz et al., 1989; Lay et al., 2006; Polet and Kanamori, 2009; Chester et al., 2013). Holes are classified into: 1) those that show sections of pelagic clay sandwiched between chert-bearing Cretaceous rocks, below, and above, covered by muddy sediments containing varying amounts of radiolarians, diatoms, and volcaniclastic and terrigenous materials, 2) 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. Base map from (Ryan et al., 2009) and site locations from GeoMapApp (http://www.geomapapp.org). Stratigraphic information at drill sites is from relevant DSDP, ODP, and IODP Site reports, respectively:
(http://www.deepseadrilling.org/i_reports.htm;
http://wwwodp.tamu.edu/publications/pubs_ir.htm;

http://www.iodp.org/scientific-publications). Sites on fence diagrams are identified in Figures 3 and 6.

Figure 3. Comparative stratigraphic sections of sites extending north east of Tohoku earthquake. C0019 is correlated to the closest reference site (436) on the incoming oceanic crust The plate boundary thrust is comprised of scaly pelagic clay at Site C0019 that is lithologically correlative to the Eocene to lower Miocene pelagic clay at Site 436. The stratigraphic sections from sites to the NE (304, 1179, and 58) suggest good continuity of the pelagic clay in this region.

Figure 4. Map of backtracked Sites IODP C0019, DSDP 436 and ODP 1149 in 10 Ma increments. Backtracking uses poles of absolute plate motions that account for movement of hotspots (Doubrovine et al., 2012). Because poles of rotation were unavailable earlier than 120 Ma, the site locations for 130 Ma and place of origin are linear extrapolations. 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 about 100 Ma (~ middle Cretaceous) to about 15 Ma (Miocene). Site 1149 has a similar path through the pelagic brown clay depositional environment, but the latter is punctuated by the presence of more seamounts than observed north of the Tohoku rupture zone.

Figure 5. A) Vertical sedimentary sequence accumulated at Sites 436 and also probably at C0019 prior to deformation. The sequence is due to lateral transport from equatorial zone of high productivity through environment of slow distal deposition of pelagic clays and finally through 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 is shown from the birthplace of Sites 436, C0019, and 1149 at about 124, 132 and 133 Ma, respectively. Age versus depth relationship for North Pacific oceanic crust from (Parsons and Sclater, 1977). Lithology and ages of Site 436 from Shipboard Scientific Party(1980).

Figure 5B) Diagram shows depth of calcite compensation depth (CCD) (Van Andel, 1975; Palike and et al., 2008) and depth of subsiding oceanic crust (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 during a short time about 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 and they are also at a depth close to the CCD at 50-55 Ma. Figure 4).

Figure 6. Lithologic columns from drilling sites south and southeast of the Tohoku earthquake. Many seamounts in this area are shallow both due to initial volcanic construction and rapid

carbonate sedimentation. Sites ODP 879 and ODP 1208 well illustrate the carbonate highs. Between seamounts the oceanic sedimentation is similar to that farther north with well-developed pelagic clay sequences, as shown at Sites 1149 and DSDP 578.

Figure 7. Tohoku earthquake shallow slip model: Diagram shows 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 of the incoming oceanic crust.

Figure 8. Seamount-induced compartmentalized earthquake failure: Cross section of subduction of oceanic crust with carbonate-covered seamounts interspersed between regions of pelagic clay (after Mochizuki et al., 2008). The 1982 earthquake initiated at edge of seamount, propagated away from it and did not produce a significant tsunami. Here, similar ~ M7 earthquakes repeat about every 20 years (Mochizuki et al., 2008). The lack of ~M7 earthquakes centered on the seamount suggests its weak interplate coupling is associated with distributed deformation of the seamount and overlying accretionary prism during the interseismic period (Wang and Bilek, 2011, 2014).

Figure 1

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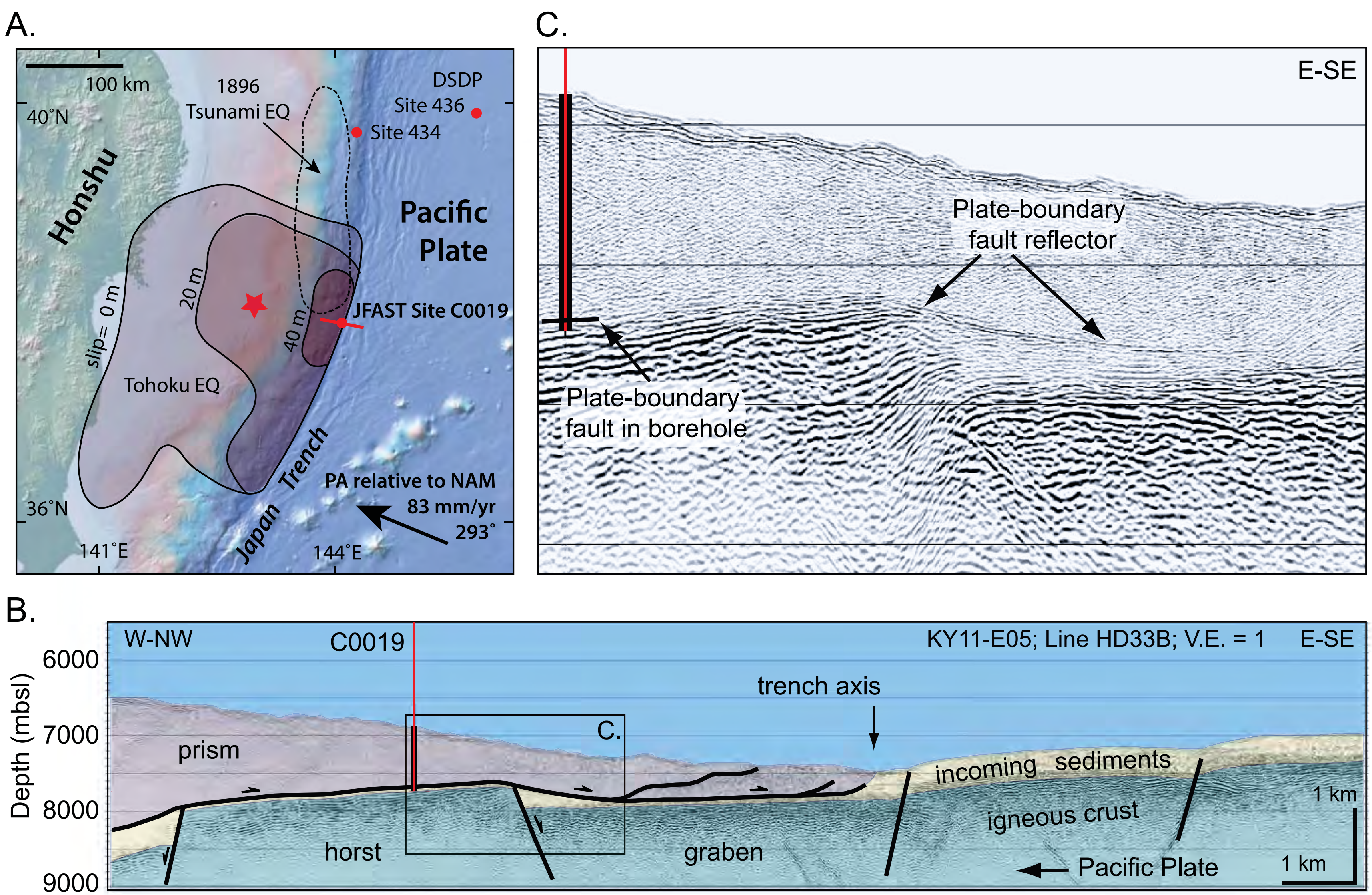

Figure 2
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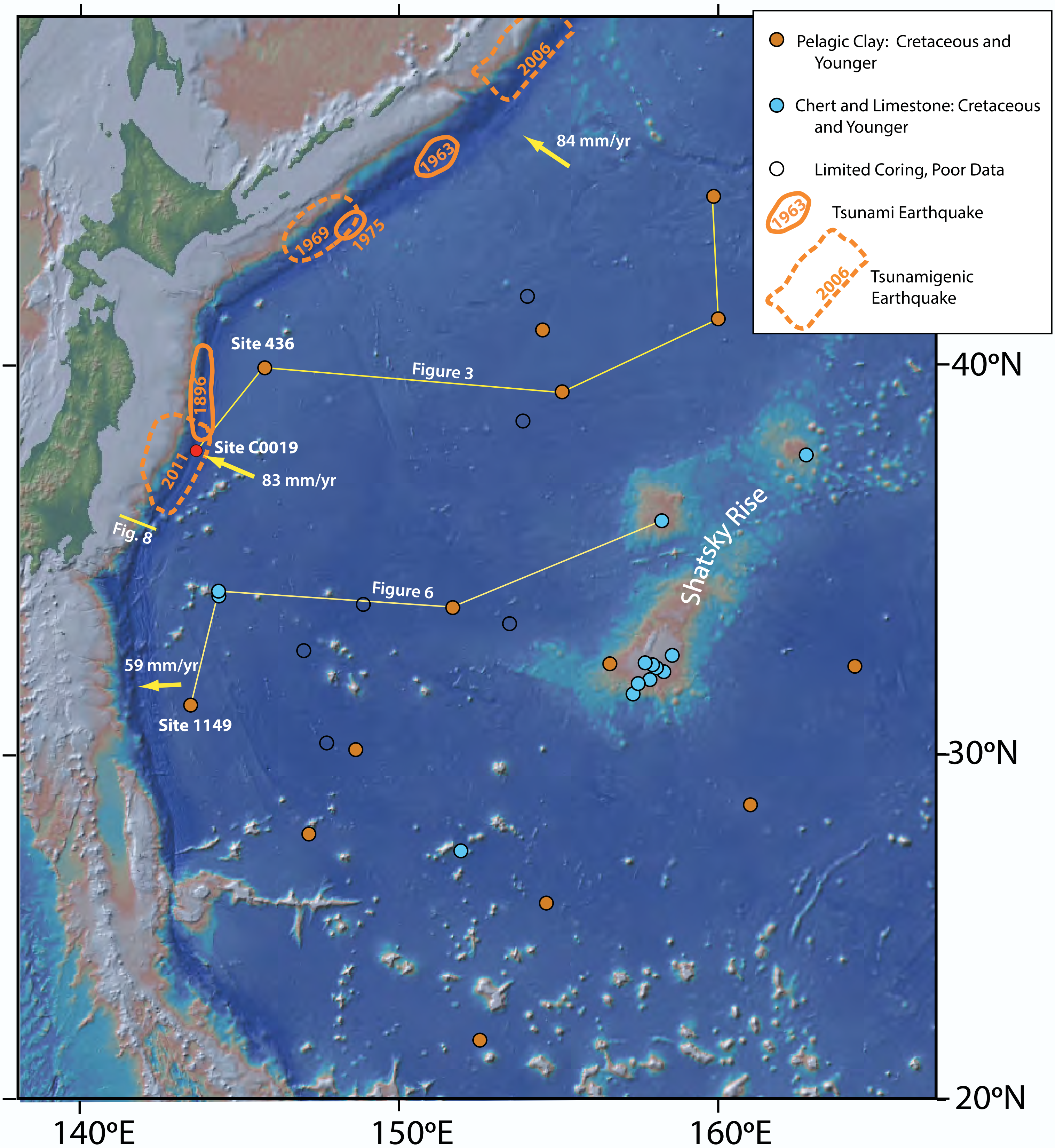

Figure 2

Figure 3

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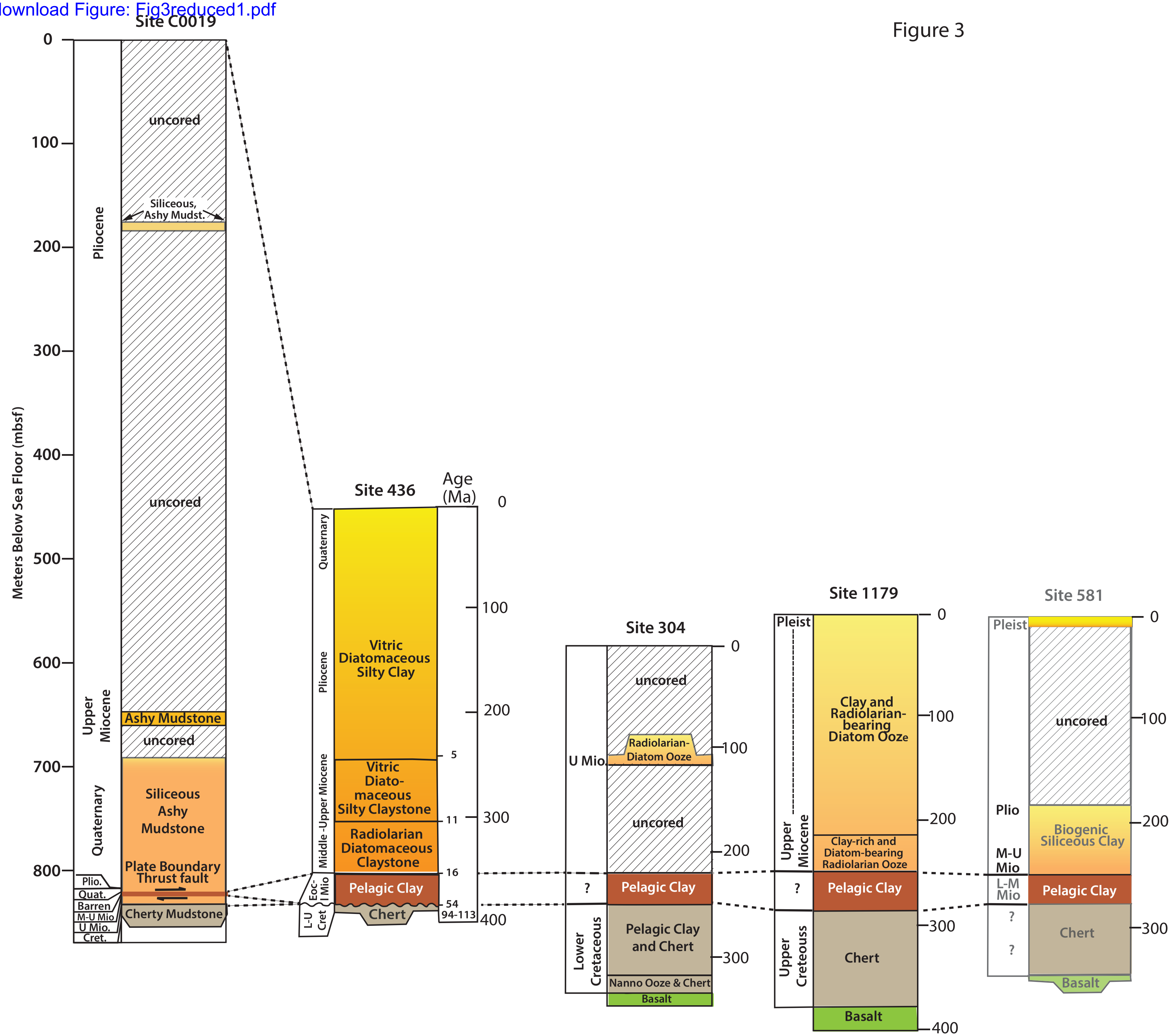

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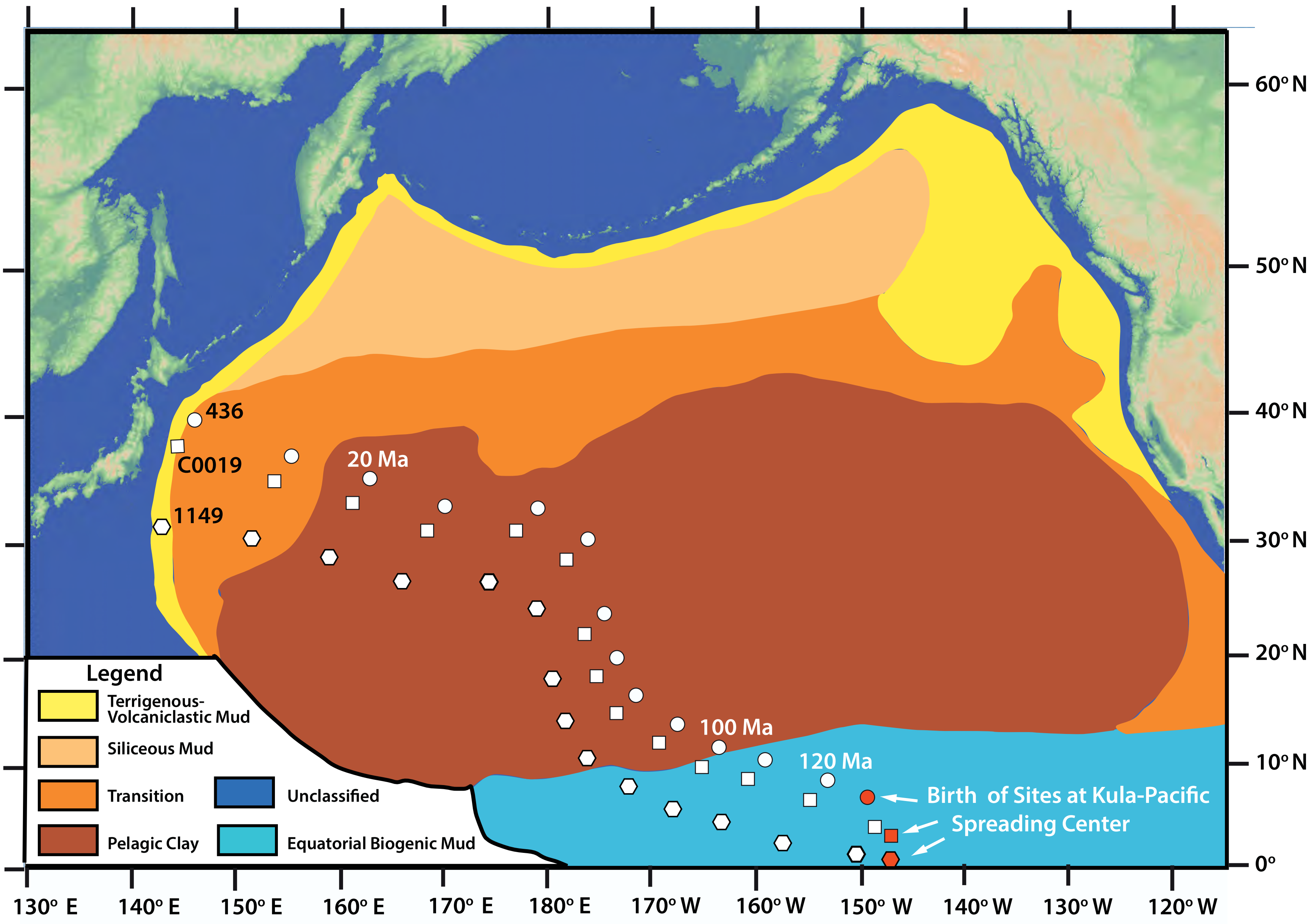

Figure 4

Figure 5a
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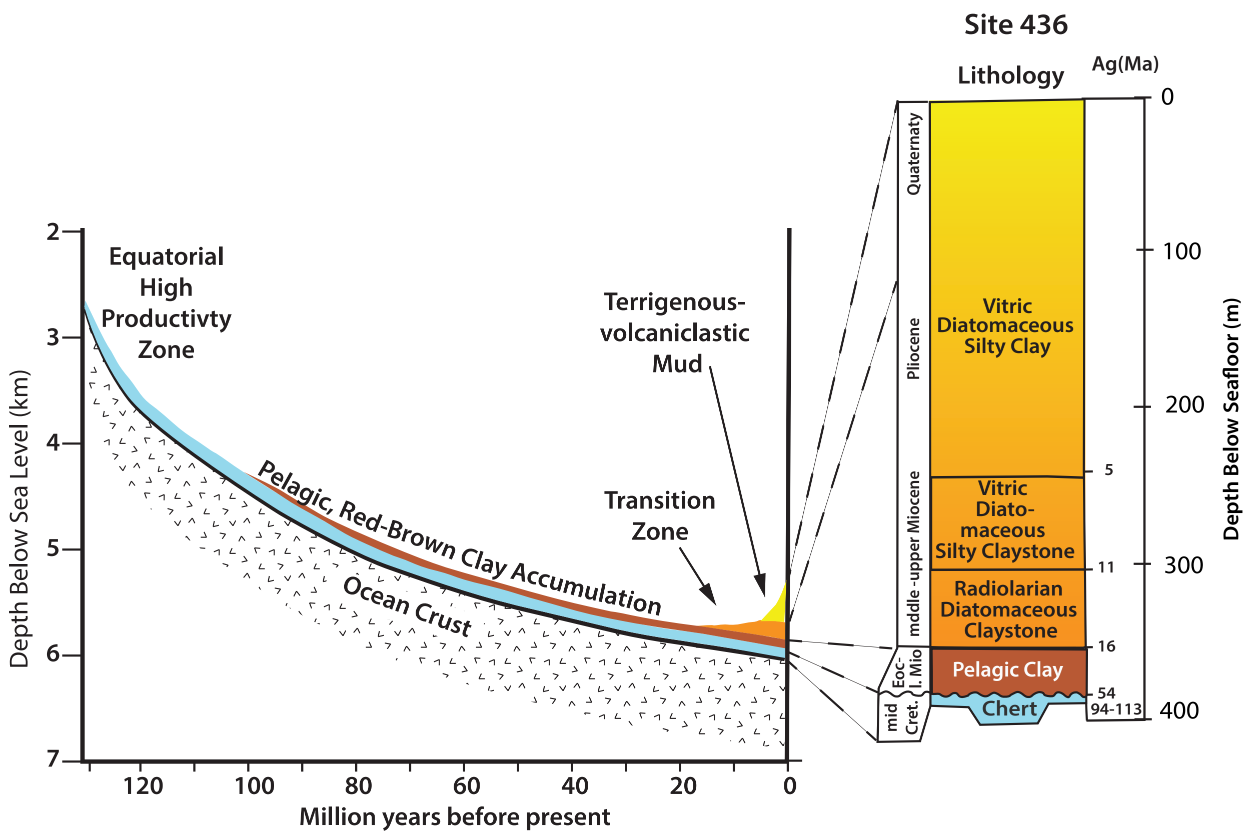

Figure 5A

Figure 5b
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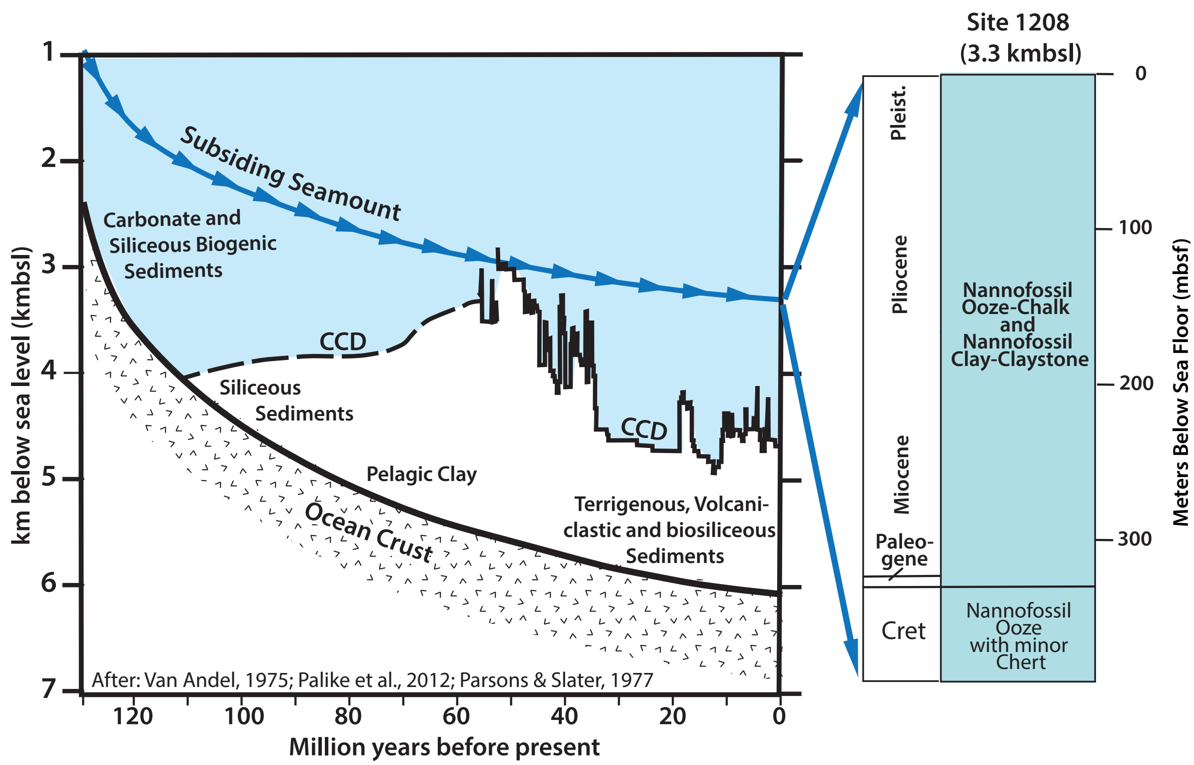

Figure 5B

Figure 6
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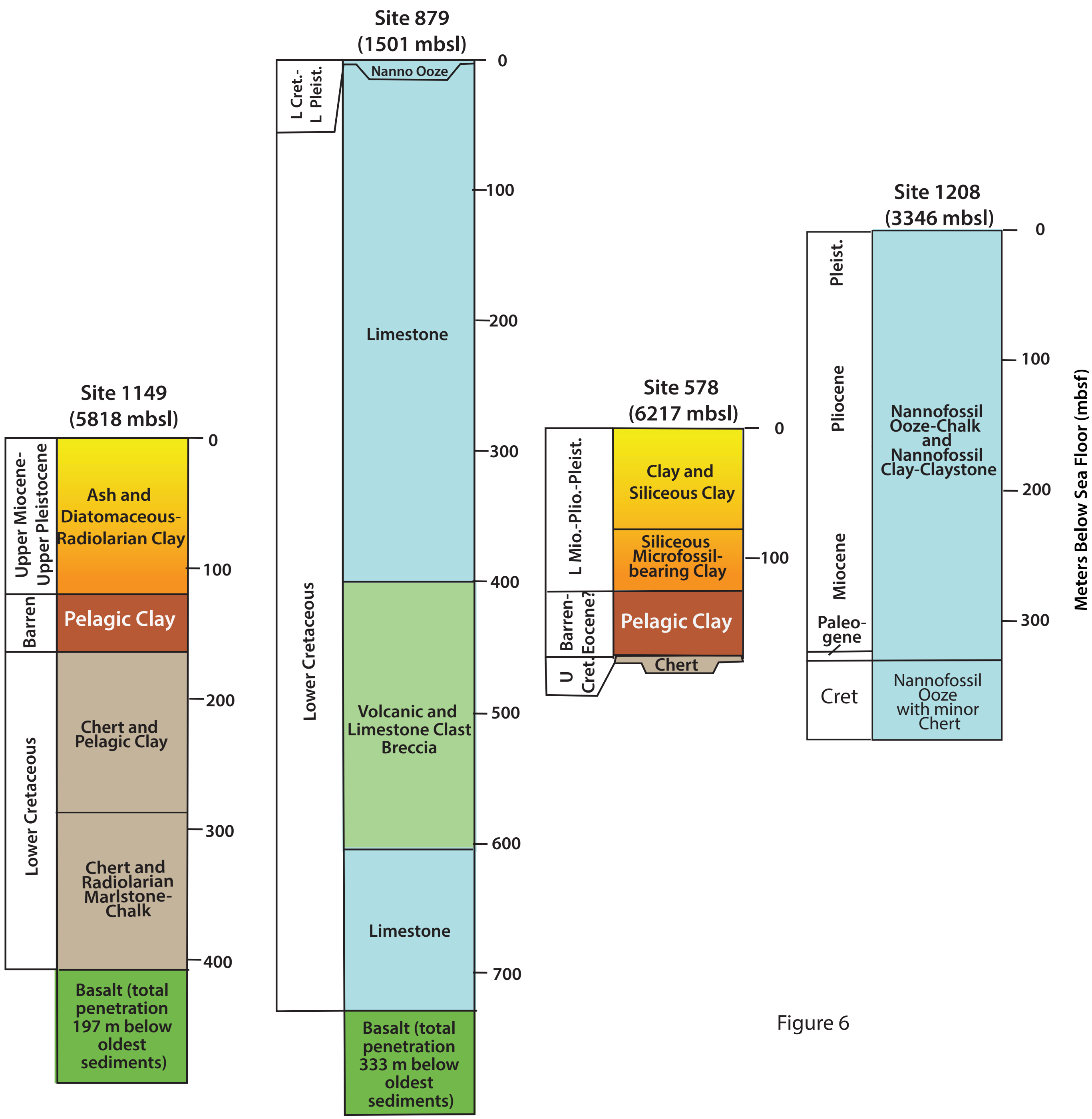

Figure 6

Figure 7
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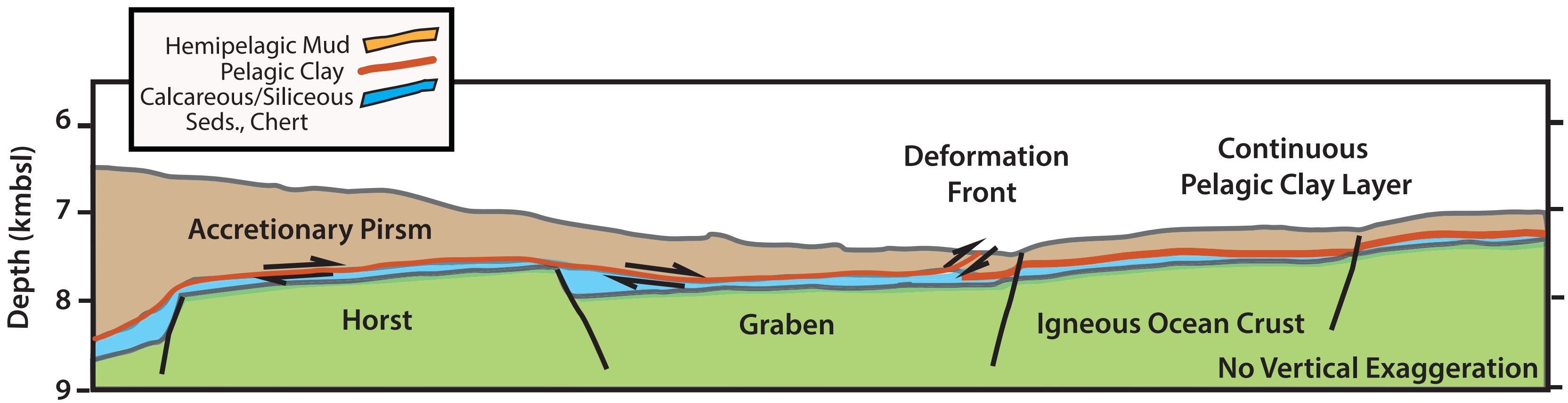

Figure 7

Figure 8

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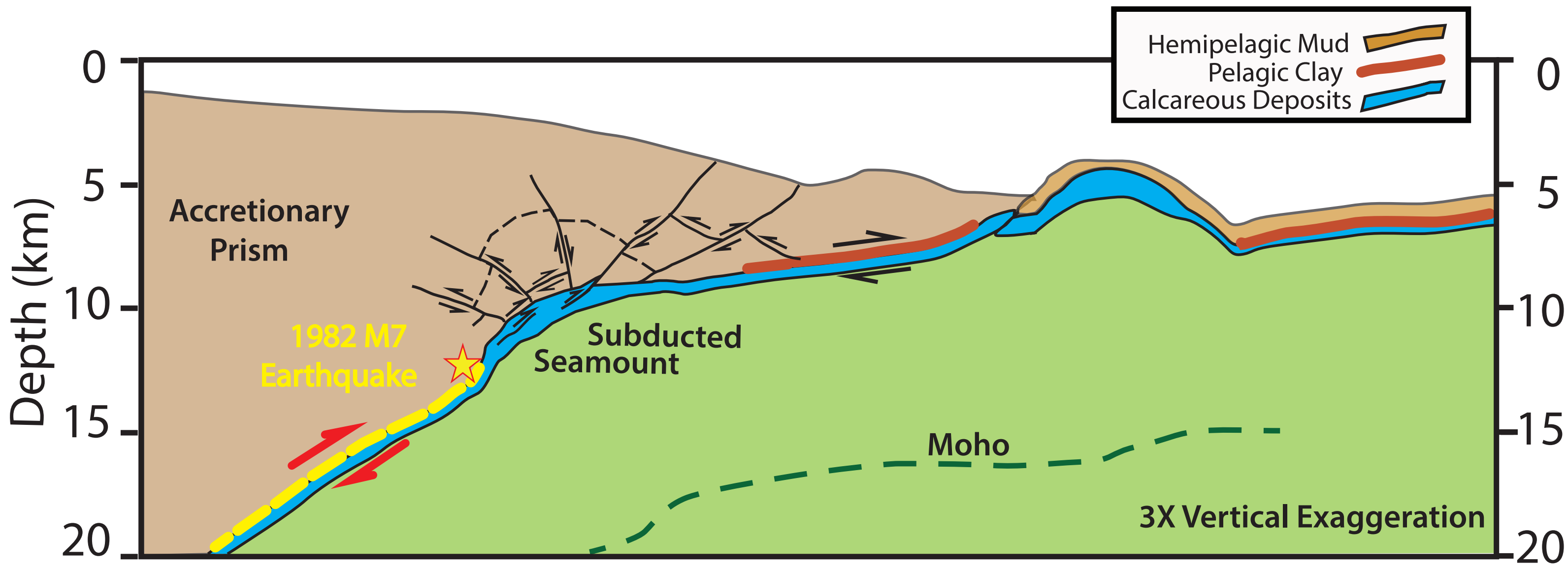

Figure 8