Forearc Slope Deformation above the Japan Trench Megathrust: Implications for Subduction Erosion

Authors:

Brian Boston^{1,*}
bboston@hawaii.edu

Gregory F. Moore¹
gmoore@hawaii.edu

Yasuyuki Nakamura²
yasu@jamstec.go.jp

Shuichi Kodaira²
kodaira@jamstec.go.jp

*Corresponding author

¹ Department of Geology and Geophysics, University of Hawai'i at Mānoa, 1680 East-West Road, Honolulu, HI 96822, USA

² Research and Development Center for Earthquake and Tsunami, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama 236-0001, Japan

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Abstract

Subduction erosion is a commonly invoked model that is used to explain the tectonic subsidence of the Japan Trench forearc slope, although other models have explained the morphology and history of the margin. New multichannel seismic reflection and bathymetric data collected after the 2011 Tohoku earthquake provide the opportunity to investigate the detailed structure of the overriding plate near the earthquake epicenter and obtain new constraints on tectonic models. We use regional-residual separation of the local bathymetry to constrain fault scarp extents and local landward-dipping forearc basins. Seismic images of these basins clearly show landward-dipping horizons in the shallow section. The strata in these basins imply a different mechanism for formation than the surrounding forearc slope, and we propose that these basins formed from local uplift. A regional basal unconformity mapped ~150 km along-trench has highly variable relief, indicating that forearc slope subsidence occurs at multiple wavelengths in response to multiple different sources. We characterize the upper to middle slope transition and propose that this region may be the landward limit of major subduction erosion and also the main region for large mass wasting. Normal faults found in this setting have maximum lengths of ~20 km, limiting their role in margin processes. Our results place constraints on the extent of major subduction erosion at the Japan Trench margin, and indicate that subduction erosion should be revisited as the sole model of formation to include additional tectonic processes.

1. Introduction

The great 2011 Mw 9.0 Tohoku earthquake produced large coseismic slip of 30-60 m (e.g., Simons et al., 2011; Ide et al., 2011; Fujii et al., 2011; Chu et al., 2011; Wei et al., 2012), creating a tsunami with local coastal heights as great as 40 m (Mori et al., 2011). The earthquake occurred where the Cretaceous Pacific Plate subducts beneath northern Honshu (Fig. 1). This subduction zone is considered an end-member case erosional margin (von Huene and Culotta, 1989; von Huene et al., 1994) defined by subsidence and normal faulting throughout the forearc slope. This tectonic erosion is thought to remove material from the base of the upper plate through hydrofracturing (von Huene et al., 2004). However, part of the subsidence may be caused by changes in plate convergence rates that alter the plate boundary geometry (Regalla et al., 2013). The morphology of the overriding plate plays a direct role in tsunamigenesis, where horizontal displacement of a steep slope can vertically displace the water column contributing to tsunami formation (Tanioka and Satake, 1996), and this type of seafloor motion is argued to have increased the tsunami height from the Tohoku earthquake (Hooper et al., 2013), revealing the importance of morphology to the margin. The coseismic slip area of large earthquakes generally correlates with the area with overlying forearc basins (Song and Simons, 2003; Wells et al., 2003; Fuller et al., 2006), but the Japan Trench margin lacks large forearc basins. Gravity analysis for the Japan Trench megathrust region indicates that the overlying plate still contributes to plate coupling and the seismogenic behavior of the margin (Bassett et al., 2016). Further characterization of forearc slope deformation in regions, such as the Japan Trench, will highlight upper plate contributions to large earthquakes and tsunami generation.

The structure and lithology of the forearc region of northeastern Japan have been previously investigated by drilling and seismic surveys (e.g., Scientific Party, 1980; von Huene

74 and Arthur, 1982; Tsuru et al., 2002; Suyehiro et al., 2003). In this region, the upper slope is
75 underlain by ~2 km thick sequences of Neogene sediments (Fig. 1) dated by drilling during Deep
76 Sea Drilling Project (DSDP) Legs 56 and 57 (Scientific Party, 1980). A regional unconformity
77 separates silicified Cretaceous basement rocks from the overlying forearc slope strata (Scientific
78 Party, 1980). This unconformity is interpreted to be a subaerial erosional surface marking sea
79 level in the Miocene (von Huene et al., 1982), and we identify it as the regional basal
80 unconformity (RBU). Below the RBU are Cretaceous claystones later accreted to form an
81 accretionary prism (von Huene et al., 1982). The youngest overlying strata extend trenchward to
82 a prominent boundary, against which a small frontal accretionary prism has formed along the
83 lower slope (Fig. 1) (von Huene et al., 1994; Tsuru et al., 2000). Forearc basins have been found
84 throughout the upper slope (Arai et al., 2014; von Huene and Arthur, 1982), with landward
85 dipping forearc basins potentially forming by slip on a listric normal fault on the landward edge
86 of the basin (von Huene and Culotta, 1989). The shallow Neogene strata are largely
87 characterized by normal faults that extend to the seafloor (Tsuru et al., 2000; Tsuru et al., 2002).
88 Regional seismic reflection surveys show that the shallow structure in the northern Japan Trench
89 forearc is similar throughout the margin (Tsuru et al., 2002; von Huene et al., 1994). However,
90 north-south wide-angle seismic refraction and reflection surveys document along-trench
91 structural variations within the overlying plate that correlate with the segmentation of the
92 interplate coupling (Fujie et al., 2013; Hayakawa et al., 2002). Observed seafloor fault scarps
93 within the lower half of the middle prism are suggested to have been created during coseismic
94 slip of the Tohoku earthquake (Tsuji et al., 2013). The frontal prism, penetrated at Integrated
95 Ocean Drilling Program (IODP) Site C0019 (Fig. 1), shows moderately- to steeply-dipping
96 accreted mudstones above a plate boundary fault zone, ~5-15 m thick (Kirkpatrick et al., 2015).

Although many seismic reflection studies since the Tohoku earthquake have focused on imaging the trench axis and deformation front, which defines the seaward boundary of the frontal prism (e.g., Kodaira et al., 2012; Nakamura et al., 2013; Boston et al., 2014), the aim of this paper is to investigate the upper forearc slope using seismic reflection surveys collected in 2011 and 2013 in order to delineate the structure of the margin. Previous surveys have studied the full margin by using widely spaced reflection lines (e.g., Arai et al., 2014; Tsuru et al., 2002). We expand on these studies by focusing near the Tohoku epicenter with a denser survey grid that allows us to investigate in greater detail the margin's complex morphology and history. In this paper, we present data from 15 seismic reflection lines combined with regional bathymetry to characterize the Japan Trench RBU, deformation styles within the forearc basins, and normal fault connectivity particularly in the middle to upper forearc slope to determine how the overriding plate has evolved over this megathrust region.

2. Methods

This project focuses on an along-trench transect above the Tohoku megathrust earthquake in the central Japan Trench region and utilizes bathymetry and seismic reflection surveys. We used a compilation bathymetry grid of the Japan Trench region from Boston et al., 2014 (Fig. 1). We applied a directional median filter that divides the filter circle into “bow tie” sectors and computes the median value for each sector (Kim and Wessel, 2008), and performed regional-residual separation of the bathymetry using a range of filter widths of 20 ± 10 km that reduced the estimated median absolute deviation for the grid. This filtering technique prevents a biased median due to a sloping regional trend, allowing for an accurate view of both the isolated short-length-scale features and the background regional bathymetry. We produced maps of regional bathymetry, median absolute deviation, regional slope azimuth, and residual bathymetry (Fig. 2).

We processed and analyzed 15 seismic reflection dip lines collected during four surveys in 2011 and 2013 on R/V *Kairei* (Fig. 1). The seismic system used a 6,000 m long, 12.5 m group interval, 444-channel hydrophone streamer cable to record seismic returns at a sampling interval of 2 ms. The source was a 7,800 in³ air-gun array fired at 50 m intervals. This acquisition geometry generated a common mid-point (CMP) interval of 6.25 m. The seismic profile grid has an average along-strike line spacing of ~10 km. MCS processing included a conventional workflow of trace edit, CMP binning, predictive deconvolution, velocity analysis, normal moveout correction, radon filter, CMP stacking, and band-pass filter (Yilmaz, 2001). We performed Kirchhoff post-stack depth migration (PoSDM) on lines D03, TH04, D05, D06, D08, D09, D13, D15, and D16. Our velocity model uses velocities based on previous local refraction and reflection studies (e.g., Tsuru et al., 2000) for the initial velocity model. We iterated the velocity model through PoSDM to a final seismic depth section that produced the clearest image. Pre-stack depth migration (PSDM) was applied to lines D02, JFD1, TH03, D11, D17, and D19, following the methods previously applied to line JFD1 (Nakamura et al., 2014) and iterating through horizon-based residual velocity analysis to produce a precise velocity model. We applied automatic gain control to all the final seismic images to enhance deeper reflections.

3. Results and Interpretations

3.1. Tilted Forearc Basins

Bathymetry analysis provides new insights into the modern forearc basin processes of the Japan Trench forearc slope (Fig. 2). The median absolute deviation provides uncertainty bounds of the regional-residual bathymetry separation where multiple length-scale features are present. Because the forearc slope contains a continuum of length scales, we selected a final range of filter widths, 20 ± 10 km, that included forearc basin features but reduced the median absolute

deviation. The separation results are assessed by the spatial distribution of the median absolute deviation between filter widths, and we find a generally low deviation except at a few locations such as the trench axis (Fig. 2B). Calculating the slope azimuth of the regional bathymetry shows a general seaward dip, except in two forearc basins (Fig. 2C). Instead, these two forearc basins have a seafloor that dips landward, suggesting a different process created these basins than the surrounding forearc slope. Whereas the landward-dipping portion of the northern forearc basin covers the majority of the basin's area (~20 x 30 km), the southern basin landward-dipping portion is small and more linear.

Seismic constraints validate our identification of these basins and provide clear images of tilted basins (Fig. 3). We divided the sedimentary column into three seismic units based on previous interpretations in the area (Arai et al., 2014) and performed a detailed line-to-line comparison of the sequences to establish continuity. Seismic lines D08 and D16 image the two landward dipping basins, whereas seismic line D11 reveals a buried landward dipping basin but with seaward dipping seafloor (Figs. 3 and 4). Line D08 images the southern basin and shows the bottom horizons onlapping onto the RBU, indicating the unconformity locally had high relief when buried by sediment. Normal faults are found to offset the seafloor within this area, indicating active deformation. However, the majority of normal faults do not offset the seafloor or shallow strata, including the overlying basin, indicating that these faults are currently not active. We do not find any clear evidence for differential compaction altering the dip direction of the seafloor, as the small amount of sediment in this basin makes this unlikely. Line D16 shows a different style of landward-dipping strata in the northern basin (Figs. 3 and 4). Here, both the oldest and youngest horizons have been tilted landward, with older, deeper horizons dipping more steeply. Additionally, the RBU follows the same geometry has the deeper overlying strata.

Folded horizons are found on the eastern edge of the tilted region. Normal faults are found beneath the basin, but do not appear within the basin. Along seismic line D11, the seafloor currently dips seaward but deeper horizons follow the geometry of an anticlinal RBU. This formed a small forearc basin in the overlying strata. These seismic lines show both a current and a past history of landward tilted forearc basins.

3.2. The Regional Basal Unconformity and Slope Sediments

The RBU has recorded the Japan Trench forearc subsidence and deformational history since the period it marked sea level. We image the RBU within a region extending ~150 km along the trench and ~110 km perpendicular to the trench. The unconformity appears as a positive high-amplitude reflection boundary (e.g., Fig. 1C) separating overlying continuous reflections from chaotic basement reflections, consistent with previous seismic reflection interpretations throughout the margin (e.g., von Huene et al., 1982; Tsuru et al., 2002). The mapped RBU includes both confident and less confident interpretations, where poor signal return or the local geology reduce deeper image quality. The seaward extent of the unconformity is difficult to locate owing to poor image quality there. DSDP Legs 56 and 57 drilled through the basal unconformity outside our survey area (Scientific Party, 1980), but DSDP Site 584 was unable to penetrate to that depth (Shipboard Scientific Party, 1986). Ocean Drilling Program (ODP) Site 1150 is near seismic line D19, and ODP Site 1151 is near seismic line D15 (Fig. 1). Dating from these two sites indicate the upper sediments are Miocene and younger in age, however, the distance between lines and well sites is too significant for accurate correlation in this tectonic setting (Suyehiro et al., 2003). Neither of these ODP sites reached the deeper RBU. The relatively small seismic grid spacing, compared to the >100 km spacing of previous studies, allows for a focused study area of the RBU along the Japan Trench margin.

The RBU morphology does not merely mimic the seafloor. We produced both a map view of the RBU (Fig. 5A), from gridding and smoothing of seismic interpretations with a 25 km Gaussian filter, and an isopach map of the sedimentary fill above the unconformity (Fig. 5B), created using the filtered bathymetry grid and the smoothed unconformity grid. The RBU exhibits >1 km relief within our survey area, whereas the seafloor remains fairly consistent on the western portion of the survey. Both high and low relief features with variable wavelengths are found throughout many seismic lines. RBU depressions of ~1.5 km deep, <40 km wide and ~30 km along strike are some of the largest. However, broader antiformal morphology is also present. Many features of the RBU are not present line-to-line indicating their length is less than the seismic grid interval. The subducting plate's structures are not found to cause consistent deformation of the RBU (Figs. 1 and 5C), unlike the processes found near the trench, where subducting normal faults clearly deform the overriding plate (e.g., Boston et al., 2014). The RBU shows a uniform increase in depth towards the east at ~50 km landward of the deformation front, generally following the trend of the deformation front's trace (Fig. 5). The isopach map reveals that the slope fill varies in thickness by ~3000 m and thins towards its seaward edge, generally within 50 km of the deformation front (Fig. 5). This thinning pattern is consistent throughout all the lines. This is also the location of a break in seafloor dip to the middle slope.

3.3 Characteristics of the Upper to Middle Slope Transition

We define the upper and middle slope at the Japan Trench margin following Arai et al. (2014), where the upper slope has a relatively flat seafloor inclined at less than 3° and the middle slope has a relatively steep slope that starts at approximately 3 km depth. Our focus is on the transition between the two slopes (Fig. 1C).

Regional-residual separation of the bathymetry grid (Figs. 2 and 6) allows for better analysis of both short-length-scale bathymetric features and the regional bathymetry at the upper to middle slope transition. The residual bathymetry largely highlights fault scarps, channels, and small-scale basins. Regional seafloor features are interpreted using both the bathymetry and seismic data to constrain structure types (Figs. 6 and 7). We find the lateral continuity of normal fault scarps is as great as ~20 km along strike, but commonly is only ~10 km. Anticlines or ridges are most commonly found near the lower slope but are also located further landward and interspersed between normal faults. This fault pattern indicates the upper to middle slope transition is not solely a normal fault boundary.

Our seismic lines show that the transition between the upper and middle slope is complex, and contains not only normal faults expected from a subduction erosion model, but also anticlines and landward-dipping strata (Fig. 7). Normal faults are found throughout the survey area. Line D05 shows a smooth seafloor with normal faults offsetting the sediment fill and a ~500 m high ridge. Line D09 reveals that normal faults offset the RBU and slope fill but do not extend up to the seafloor. Basin fill thickness of ~1 km is found near the center of the profile where the seismic amplitude of the RBU becomes weaker and thus forces a less confident interpretation. At line D17, the upper to middle slope transition is sharp, with thickening of the upper slope sediment fill until a steep slope break, after which the slope fill decreases from ~2.5 km thick at the seaward edge to <1 km thick over a distance of ~5 km. At the slope break, the seafloor and the RBU are offset by multiple normal faults. This steepening of the seafloor and thinning of sediment fill may be caused by submarine landslides (e.g., Kawamura et al., 2012). Line D19, ~12 km north of D17, shows a very different morphology. Line D19 shows slope fill that is heavily deformed by normal faults like in D17, but the RBU remains generally

continuous. An anticline on the RBU appears to have a deeper landward-dipping reflection beneath it and deforms the seafloor. Slope fill thickens seaward on line D19 until this anticline and then thins seaward. The acquisition geometry of line D19 within this transition zone has a kink in it, caused by the need to avoid debris in the water, and this kink may cause seismic artifacts. However, line D19 is not the only line in which anticlines and landward-dipping beds are found. Line D03 shows a large anticline on the seaward edge (Fig. 7), ~30 km west of the deformation front. This anticline is ~4-6 km long along strike and contains a local bathymetric high (Fig. 6). Line D13 shows the seafloor slopes seaward, to the east, but bedding dips landward from the RBU to the overlying forearc basin and has a similar deformational pattern to the basin fill in seismic line D11 (Figs. 3 and 4). The nearby location of these basins and similarities in tilting suggests that this previous tilting event was continuous for greater than 10 km along-trench. The basin in which lines D11 and D13 are located is bounded to the north by a local bathymetric high where ODP Site 1151 is located (Figs. 3 and 1). This separates the basin of D11 and D13 from the northern basin of line D16, which has a landward-dipping seafloor. Furthermore at line D13, an anticline of ~2.5 km in width is located on the seaward edge of the landward-dipping strata (Fig. 7), but the RBU contains a broader anticline of ~15 km wide in this area. Additionally, the seaward edge of the RBU across the survey area generally contains weaker amplitudes and is less continuous, causing a less confident interpretation for the region (Fig. 7). This reoccurring feature may be from changes in the depositional pattern or increased deformation from faults and folds in the region. These disparate seismic profiles across the survey area reveal a complex and nonuniform transition between the upper and middle slope. Both seismic and bathymetric data show normal faults with anticlines interspersed between them, in contrast to previous interpretations of the margin.

4. Discussion

Our results indicate that subduction erosion is not the sole driving force for the deformation found along the Japan Trench upper slope. The subduction erosion model predicts a landward progression of subsidence as basal erosion migrates arcward with time. Instead, we do not find a consistent deformational pattern for the RBU at the upper slope. The regional subsidence pattern of the Japan Trench margin can be estimated from subducting plate geometry changes due to accelerations in plate converge and decreased plate buoyancy due to extension associated with the opening of the Sea of Japan with peak local convergence rates occurring 10 to 30 Ma (Regalla et al., 2013). In the Miocene, the Japan arc and backarc experienced a change from trench-perpendicular extension to shortening (Kato et al., 2006). This onshore shortening may have extended seaward to the upper slope basins (e.g., Regalla et al., 2013), and benthic foraminifera assemblages further indicate shallowing and uplift of the forearc seafloor since 3.5 Ma (Arthur et al., 1980). We find both modern and buried basins with strata that dip landward in response to local uplift at the seaward side of each basin, as multiple seismic lines display anticlines in both the RBU and overlying sediments on the seaward edge of these basins (Fig. 3). A subducting seamount is not found on the subducting plate and does not appear to be the cause of these basin formations, with the major subducting features being a horst and graben system (Figs. 1 and 5). Whereas subducting normal faults influence the frontal prism's decollement (Boston et al., 2014), at depth, the subduction plane has been previously interpreted to be above the top of such features (von Huene and Culotta, 1989). Similar basins found north of our survey area were proposed to be formed by a listric normal fault on the landward edge of the basin (von Huene and Culotta, 1989). However, we do not find evidence for a basin-forming listric fault system in the sediment column nor RBU. Such a feature potentially has a limited along-trench

extent like structures found within our survey area. Normal fault populations at the Japan Trench upper slope have also been suggested to indicate subduction erosion (e.g., von Huene et al., 1994). However, many of the normal faults found in our survey area do not offset the seafloor or overlying forearc basins and thus are not currently active (Figs. 4 and 7). Instead, the proximity of both normal faults and thrusts may indicate periods of alternating faulting style or periods of variable fault formation. The changes in subsidence rates and convergence rates for the upper slope may influence the different faulting styles found along the margin (Scientific Party, 1980; Regalla et al., 2013). These results indicate that subduction erosion needs to be reconsidered as the sole driving force of the deformation found at the Japan Trench upper slope.

The middle slope shows a more consistent deformational pattern than the upper slope. The RBU consistently dips seaward and slope fill consistently thins at the middle slope (Fig. 5), whereas the upper slope lacks such uniformity. Additionally, an increase in chaotic reflections in the middle slope may indicate highly deformed strata there. The greater amounts of subsidence at the middle slope cannot fully be explained through changes in plate convergence rates and may be from subduction erosion (Regalla et al., 2013). Therefore, these results indicate a landward limit to major subduction erosion.

Many of the deformational processes at the middle slope are still unknown due to poor imaging there. Subducting siliceous sediments at the Japan Trench have a maximized dehydration rate zone of ~50-60 km from the deformation front (Kimura et al., 2012). This location is near the middle to upper slope boundary, suggesting that this water influx may cause hydrofracturing of the overriding plate and subduction erosion (von Huene et al., 2004) within the middle slope and diminishing on the upper slope. Other velocity models have found a sharp bend in the subducting Pacific Plate, where the subduction angle steepens by $\sim 8^\circ$, and the

bending axis located near the upper to middle slope (Fujie et al., 2006; Ito et al., 2005). However, this apparent bend could also be caused by a rough plate interface or earthquakes occurring on subfaults off the main plate boundary fault, with no bend required to explain the data (Zhan et al., 2012). Therefore, the role in the subducting plate bend on the middle slope deformation is still unclear.

The middle slope may further play an important role for mass wasting. Previous bathymetry analysis, deep-sea submersible observations, and tsunami modeling indicate potential submarine landslide locations at the middle slope region that may have impacted tsunami generation during the Tohoku event (Kawamura et al., 2012; Tappin et al., 2014). Seafloor steepening and slope fill thinning at the upper to middle slope transition suggests seafloor erosion is present along the middle slope (Figs. 5 and 7). Additionally, seismic reflectors become chaotic within the middle slope implying further deformation. We find no direct evidence of major mass wasting events on the upper slope within our seismic resolution, but middle slope erosion confirms that the upper to middle slope transition is the landward boundary for large mass wasting events.

A regional landward-dipping normal fault at the upper to middle slope transition has been inferred to create a pop-up structure during concurrent rupture of both the plate boundary fault and the normal fault (Tsuji et al., 2011; Tsuji et al., 2013). However, this interpretation requires that the normal fault extends horizontally several tens of kilometers in order to vertically extend down to the plate boundary at ~12 km. Our interpretations show that this normal fault has only limited (~10 km) lateral continuity in our survey area (Figs. 6 and 7). Additionally, the other active seafloor breaching faults also lack regional connectivity, but we still do not fully understand how the deeper faults propagate throughout the margin. After the 2011 Tohoku

earthquake, normal fault type mechanisms were widely distributed in the overriding plate (Asano et al., 2011), however, a densely-spaced ocean bottom seismograph survey revealed a 45-km-wide aseismic wedge for the overriding prism's toe (Obana et al., 2013). This area also shows a clear velocity contrast between low velocity accreted sediments and a higher velocity backstop for seismic line JFD1 (Nakamura et al., 2014). This presumed backstop interface is within the middle slope, but does not appear to correlate with a bounding normal fault. Due to the range of deformational styles at the upper to middle slope transition and lack of regional fault connectivity, normal faults at the upper to middle slope transition, and their potential pop-up structure, should not be considered an indicator of a regional tsunami source area at the Japan Trench margin.

5. Conclusions

We provide new seismic reflection profiles and interpretations of the Japan Trench margin that investigate tectonic processes in an ~150 km along-trench region. We find that the middle slope has consistent thinning of slope fill, steepening of the seafloor, and chaotic reflections, signifying a region of major mass wasting events. The upper to middle slope transition shows both extensional and shortening features that lack regional connectivity, indicating that individual normal faults play a limited role in regional deformational processes at the Japan Trench margin. We observe that the regional basal unconformity contains a variable pattern of deformation and that uplift occurred in selected regions, greatly differing from the pattern found at the middle slope. This pattern indicates that a purely erosional model is not appropriate for the Japan Trench margin and that additional tectonic activity has deformed the region, which may have implications for similar behavior at other margins.

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Figure Captions

Figure 1. A. Tectonic setting of the Japan Trench. The red box is the location of Figure 1B, the yellow star shows the 2011 Tohoku earthquake epicenter (Chu et al., 2011), and white arrows show the convergence direction of the Pacific Plate – PP=Pacific Plate and EP= Eurasian Plate. B. Bathymetry map of the study region. Black lines are seismic profiles with white sections displayed in Figure 3. White dashed curve is the deformation front (Boston et al., 2014). Grey contours show coseismic slip area for the 2011 earthquake (Wei et al., 2012). Diagonally shaded areas are identified as isolated basins (Arai et al., 2014). Green circles are ODP Sites and red circle is IODP Site C0019. The star is the earthquake epicenter. Red box is the location of Figure 6. C. Seismic profile D17 with forearc slope morphology, the regional basal unconformity, and subducting Pacific Plate and normal faults marked. The lower slope is the general location of the actively accreting prism.

Figure 2. Regional-residual separation of bathymetry. White lines are the seismic profiles and the red or blue dashed line is the deformation front (Boston et al., 2014). A. Regional filtered bathymetry. B. Distribution of median absolute deviation (MAD) values from results in Figure

2A. C. Slope azimuth of the regional bathymetry. Blue circles highlight two landward tilted forearc basins. D. Residual bathymetry.

Figure 3. Seismic profiles of landward-dipping basins with locations in Figure 1. The regional basal unconformity is at the top of the green region. Red boxes are locations of the basins shown in Figure 4. Dashed black lines are interpreted horizons, and gray lines mark seafloor breaching normal faults. The seafloor above forearc basins of lines D08 and D16 dip landward with underlying strata also dipping landward. The RBU of line D11 contains an anticline that is also found in the overlying strata, creating a thicker basin west of the anticline.

Figure 4. Shallow basins at the Japan Trench forearc. Locations are in Figure 3. The top of the blue region marks the onlapping surface. Normal faults (gray lines) in lines D08 and D16 do not propagate through the overlying basin strata. Line D11 contains buried landward strata following the geometry of deeper horizons.

Figure 5. Map view of the RBU, forearc slope sediment thickness map, and Pacific Plate with the seafloor shaded relief plotted on top. A. Smoothed surface of the RBU. Grey lines are the seismic profiles to show interpretation constraints. Black dashed line in all plots is the shape of the deformation front shown for comparison with local trends (note that the deformation front is located 50 km to the east). B. Isopach map of sediments above RBU. One general trend of thinning near the eastern edge is found throughout the region. However, the overall region shows multiple thicker basins. C. The subducting Pacific Plate smoothed surface from the PSDM lines.

Figure 6. Bathymetry and residual bathymetry at the upper to middle slope boundary and structural interpretations. The location of this region is shown in Figure 1B. Black lines are seismic lines with the white sections presented in Figure 7. A. Bathymetry with seismic line

names. B. Residual Bathymetry. C. Seafloor breaching large-scale features constrained from seismic profiles.

Figure 7. Seismic profiles of the upper to middle slope transition (left column) and general interpretations (right column) with profile locations in Figure 6. The top of the green region marks the regional basal unconformity with dashed regions having lower certainty. Gray lines are normal faults. The profiles are in the general same location from north to south (Fig. 6), but show a range of morphologies for the area.

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543 **List of Abbreviations**

544 DSDP Deep Sea Drilling Project

545 IODP Integrated Ocean Drilling Program

546 ODP Ocean Drilling Program

547 RBU Regional Basal Unconformity

Figure 6