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Subducting plate geology in three great earthquake ruptures of the western Alaska margin, Kodiak to Unimak

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ABSTRACT

Three destructive earthquakes along the Alaska subduction zone sourced transoceanic tsunamis during the past 70 years. Since it is reasoned that past rupture areas might again source tsunamis in the future, we studied potential asperities and barriers in the subduction zone by examining Quaternary Gulf of Alaska plate history, geophysical data, and morphology. We relate the aftershock areas to subducting lower plate relief and dissimilar materials in the seismogenic zone in the 1964 Kodiak and adjacent 1938 Semidi Islands earthquake segments. In the 1946 Unimak earthquake segment, the exposed lower plate seafloor lacks major relief that might organize great earthquake rupture. However, the upper plate contains a deep transverse-trending basin and basement ridges associated with the Eocene continental Alaska convergent margin transition to the Aleutian island arc. These upper plate features are sufficiently large to have affected rupture propagation. In addition, massive slope failure in the Unimak area may explain the local 42-m-high 1946 tsunami runup. Although Quaternary geologic and tectonic processes included accretion to form a frontal prism, the study of seismic images, samples, and continental slope physiography shows a previous history of tectonic erosion. Implied asperities and barriers in the seismogenic zone could organize future great earthquake rupture.

INTRODUCTION

Some great earthquakes rupture the same subduction zone segments repeatedly, indicating a geologic control. Among the proposed controls of rupture in subduction zones are mate-

rial and relief along the plate interface. Commonly, (1) plate interface material is inferred from trench sediment input to the subduction zone (cf. Underwood, 2004; Morgan and Ask, 2004), and (2) morphologic features on the lower plate are inferred from the adjacent ocean basin character and aftershock distribution (Das and Watts, 2009; Bilek et al., 2003). Seamounts and fracture zones on the subducting plate locally correlate with asperities and barriers to earthquake rupture (Kodaira et al., 2000; Watts et al., 2010). Subducted material and relief inferred from tectonic history are here compared with aftershock seismicity from three great earthquakes in the Alaska subduction zone to help understand past and possible future earthquake rupture. We first reconstruct a Gulf of Alaska plate convergence history over the time it takes for the lower plate to subduct to the volcanic arc. Then we summarize active tectonic deformation where long ridges, seamount chains, fracture zones, and deep-sea fans enter the subduction zone beneath western Alaska. We draw attention to collocated subducting features and earthquake asperities, barriers, and aftershocks, and present a map of subducting relief and possible material distribution along the plate interface indicated by tectonic and geologic features.

Our primary objective is to relate the subducting structure and sediment bodies to earthquake ruptures. Some features of the subducting plate occur at the limits of aftershocks distribution following great earthquakes. This collocation indicates a possible control on rupture length and also the collocation of seamounts and fracture zones with the region of high moment release on the Kodiak rupture during the 1964 great Alaska earthquake. Such correlations can form the basis of understanding cause and effects between subduction zone earthquakes and plate interface geology. It also becomes clear that structures of both plates may be involved.

For readers familiar only with older observations, the erosional tectonic character of the Alaska margin is brought forward to counter the oft-cited accretionary character. The difference in earthquakes and tsunamis along accretionary as opposed to erosional margins is beginning to emerge in the scientific literature. Bilek (2010), for example, observed that transoceanic tsunamis are more frequently sourced from erosional rather than accretionary margins. However, one exception is the Alaska subduction zone, which was assumed to be accretionary, yet has sourced devastating tsunamis. The Alaska margin was initially characterized with industry data across the Pamplona thrust zone by Stoneley (1967). The Pamplona thrust zone, located immediately northeast of the Alaska Trench (Fig. 1), is an extension on to the continent of Alaska Trench-plate convergence (Bruns, 1984; Worthington et al., 2008). Deformed sediment in the Pamplona zone has not been transferred from the lower plate, but is thrust-faulted shelf sediment. Seely (1977) published industry-acquired seismic images of the Kodiak margin in which landward-verging structures were interpreted as obducted trench sediment. From these observations, Dickinson and Seely (1979) proposed accretionary structure for the Kodiak segment of the Alaska margin. However, the deformed sediment was not transferred from the trench axis. More recent data are summarized here to show that although the current margin has a local 5–15-km-wide accretionary frontal prism, the earlier Quaternary margin was largely erosional.

GULF OF ALASKA OCEAN BASIN PLATE FEATURES AND TECTONIC HISTORY

The western Gulf of Alaska ocean basin is bordered on the north by the Yakutat terrane (YT) and on the west by the Alaska Trench

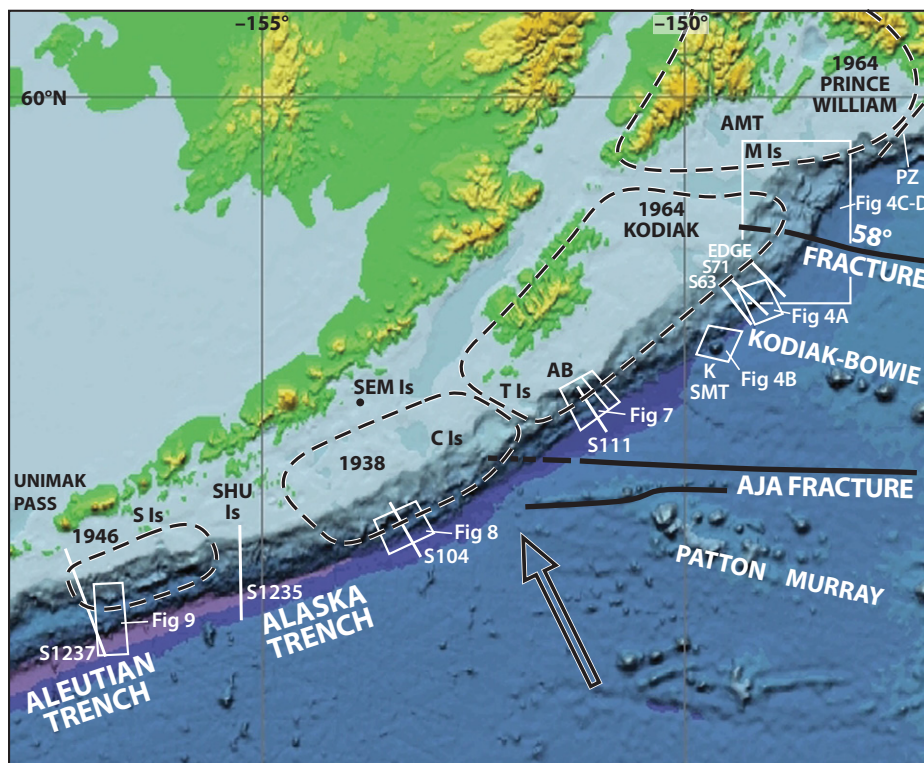


Figure 1. Map of the western Gulf of Alaska ocean basin and the Alaska convergent margin. Dashed lines enclose aftershock areas of the 1938, 1946, and 1964 great earthquakes. The Prince William and Kodiak ruptures are separated to emphasize the two main asperities of the 1964 event. The width of the Kodiak margin from the trench to the volcanic arc narrows southwest from the Kenai Peninsula to one-third this width at Sanak Island. The wider subducted plate is ~10 m.y. old beneath the northeastern volcanoes, whereas in the southwest it is only ~3.5 m.y. old. Large arrow indicates convergence vector at 64 mm/yr. S prefix is given to seismic lines and original cruise line numbers. Seismic data of lines 1237 and 1235 were acquired by RV Ewing; seismic data of lines 111, 71, and 63 were acquired by RV Lee. Field data for both is archived at the US Geological Survey in Menlo Park, California, USA. M Is—Middleton Island; K SMT—Kodiak Seamount; C Is—Chirikof Island; T Is—Trinity Islands; SEM Is—Semidi Island; SHU Is—Shumagin Islands; S Is—Sanak Island; AMT—Amatuli Trough; AB—Albatross Bank; PZ—general area of the Pamplona zone.

(Fig. 1). We distinguish between the continental Alaska and island arc Aleutian Trench because newer geophysical data show a distinct structural difference between them, as is discussed further in this paper. In the central Gulf of Alaska, the YT underthrusts Alaska on land along the Chugach–St. Elias thrust fault, which continues across the shelf and slope along the Pamplona fold and thrust zone that joins the Alaska Trench (Plafker, 1987; Worthington et al., 2008). A distinctive magnetic anomaly along the trailing flank of the YT, the slope anomaly, can be traced 350–400 km down the Alaska subduction zone (Eberhart-Phillips et al., 2006). The Kodiak-Bowie and Patton-Murray Seamount chains (Fig. 1) are south of the YT. These seamounts are 1–3 km high on top of broad ridges formed by intrusions into older ocean crust. Adjacent

fracture zones are defined by offset magnetic anomalies (Schwab et al., 1980; Atwater, 1989; Maus et al., 2009) and by free-air gravity anomalies (Andersen et al., 2005). The ridges and fracture zones are inferred to continue beneath the forearc to the subducted northern part of the great magnetic bight (Atwater, 1989), because (1) south of the Patton-Murray ridge, similar fracture zones cut a regular pattern of older

magnetic anomalies to the magnetic bight, and (2) the ridges and fracture zones are continuous across the North Pacific, so it is likely that exposed ocean crustal patterns extend down the Alaska subduction zone.

Collision of the YT (Fig. 2) and subduction beneath central Alaska is coeval with rapid uplift of the Chugach–St. Elias Mountains. Uplift and exhumation measured with thermochronometry (Spotila et al., 2004; Berger et al., 2008; Enkelmann et al., 2009) are coeval with increased sedimentation throughout the Gulf of Alaska (Fig. 3) (Rea and Snoeckx, 1995). Developing a basis for inferring geology of the lower plate subducted beneath the Alaska margin involves reconstructing migration of the YT. Whether the YT is coupled to the Pacific plate or is an independent microplate is controversial. Here, it is argued that inasmuch as the YT southern flank is truncated by the Fairweather fault on the east, and no tear faults above the YT are present on the west, extensive strike-slip displacement is unlikely (Bruns and Carlson, 1987; Eberhart-Phillips et al., 2006). East of the Pamplona zone the YT linear southern boundary is assumed to be a fossil transform fault and along most of its length it has essentially been coupled to the Pacific plate for the past 10 m.y. (Bruns and Carlson, 1987; von Huene et al., 1987; Gulick et al., 2007). The importance of that coupling here is that it simplifies reconstruction of a plate tectonic history (Fig. 2).

Coupling is also consistent with an ~15 km abrupt change of crustal thickness that occurs across the Transition fault without evidence of sediment subduction (Christeson et al., 2010). The 2.5–4.5-km-deep trough that flanks the Transition fault contains more than enough sediment to form an accretionary prism and fill a subduction channel (Shor, 1965; Stevenson and Embley, 1987; Christeson et al., 2010; Reece et al., 2011). Any convergence must be less than the resolution of geophysical data because it is not imaged despite many seismic transects. Segments of the Transition fault are covered by undeformed sediment that is ~2 m.y. old (Bruns and Schwab, 1983, horizon A-1).

Sedimentation in the Gulf of Alaska is consistent with a coupled YT and Pacific plate. Three scientific drill holes of the Deep Sea Drilling Project (DSDP), and Ocean Drilling Program

Figure 2 (on following page). Plate tectonic history of the Gulf of Alaska during the past 10.6 m.y. superimposed on present geographic features. Black dots indicate the position of a point at the present juncture of the Alaska Trench and the Yakutat terrane (YT) trailing flank moved back in time according to the plate migrations of Stock and Molnar (1988). Black line indicates the 58° fracture; KOD—Kodiak group of islands; SF—Surveyor fan; KB—Kodiak-Bowie Seamount chain; PM—Patton Murray Seamounts; ZF—Zodiak fan.

Alaska margin geology

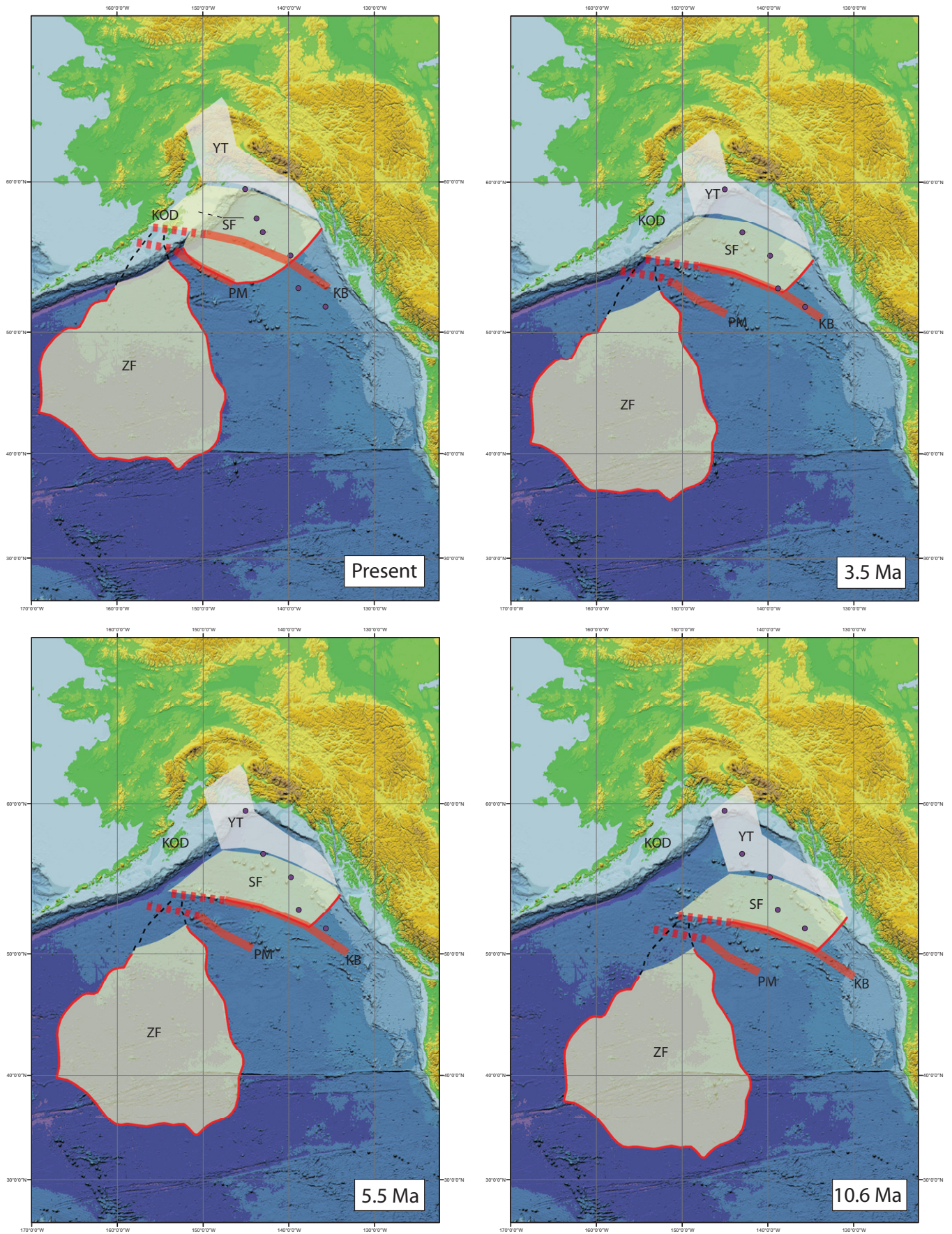
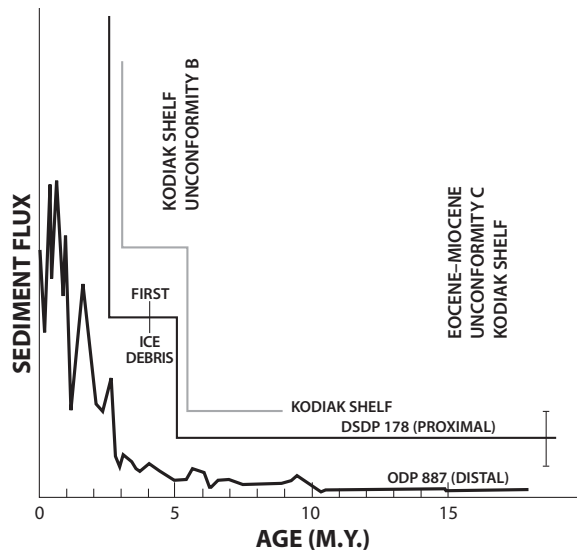


Figure 3. Increase in terrigenous sedimentation in the past 3 m.y. Site 178, drilled during Deep Sea Drilling Project Leg 18 (DSDP, 1971) is shown as orthogonal straight lines between paleontological age determinations. Three other sites from Leg 18 trend similarly (von Huene and Kulm, 1973). Ocean Drilling Program (ODP) Site 887, a distal site, was drilled on Patton-Murray ridge during ODP Leg 145 (Rea and Snoeckx, 1995). Gray line represents ages of unconformities in Kodiak shelf drill hole KSSD-2 (Turner et al., 1987). Vertical axis is nondimensional and lines are grouped to show pattern of increased sedimentation. Proximal sites show increasing sedimentation earlier than the distal site.



(ODP) in the deep Gulf of Alaska are currently at proximal to distal distances from the Chugach–St. Elias sediment source area (Fig. 3). On DSDP Legs 18 and 19 (1971), carbonate microfossil recovery was sparse and assemblages sufficient to sharply define ages were few compared with the nearly 100 or more determined with better technology on ODP Leg 174 (Rea and Snoeckx, 1995). The sedimentation history developed from ODP Leg 174 Site 887 cores resolved individual glacial periods superimposed on a general sediment increase. Rates of sedimentation from older drilling with wider spaced paleontological age control (Fig. 3) confirm the general sediment increase. The industry-acquired Continental Offshore Stratigraphic Test (COST) drill hole on the northeast Kodiak shelf gave 60, 120, and 500 m/m.y. rates of deposition during the Late Miocene, Pliocene, and Pleistocene, respectively (Site KSSD 2; Turner et al., 1987) (Fig. 3). Shelf drill sites are stationary with respect to their sediment source, whereas those on the lower plate migrated toward the source area. Onshore outcrops show sedimentation attributed to increased continental denudation (Lagoe and Zellers, 1996). Thermochronometry records (Spotila et al., 2004; Berger et al., 2008; Enkelmann et al., 2009) indicate a phase of rapid uplift in the past 3–4 m.y. superimposed on earlier general uplift. This temporal history from various sources is consistent with a coupled YT and Pacific plate history.

Migration of the YT and Pacific plate through the Gulf of Alaska (Fig. 2) was constructed using the Stock and Molnar (1988) plate vectors. The diagrammatic YT area is constructed from studies of seismicity and crustal data (Eberhart-Phillips et al., 2006; Fuis et al., 2008;

Abers, 2008) (Fig. 2). A plate tectonic history is illustrated with snapshots at 3.5, 5.5, and 10.6 Ma (Fig. 2). Reconstructing central Alaskan tectonics is beyond the scope of this study, and although it would modify our approximation of tectonic history, it would not have a first-order effect.

In the reconstruction, at 10.6 Ma, the YT leading edge was at the current central Gulf of Alaska margin position. The Surveyor deep-sea fan occupied the low area between the YT trailing flank and the Kodiak-Bowie basement ridge (Fig. 2; Stevenson and Embley, 1987; Reece et al., 2011). The Kodiak-Bowie ridge is extended to the reconstructed head of the Zodiak fan (Fig. 2). At the head of the fan, a stable sediment gateway is required to source this huge fan from one point for 10 m.y. (Stevenson and Embley, 1987). A current gateway of this type is the narrow notch in the Blanco Fracture Zone that restricts sediment flow at the head of the Tuffs fan (Normark and Reid, 2003).

In the 5.5 m.y. snapshot, the westernmost edge of the YT subducted beneath the current Alaska margin shelf (Fig. 2). Terrane subduction probably eroded the margin, sending erosional debris into the trench axis from an unstable slope. The Kodiak-Bowie and Patton-Murray ridges entered the Aleutian Trench, and local erosion of the margin would be expected as they migrated along it. On the shelf, an unconformity across the seaward flank of Stevenson Basin and on the seaward flank of Albatross Basin (horizon B, Fisher and von Huene, 1980), indicate uplift of the slope and outer shelf seafloor.

In the 3.5 m.y. snapshot, YT subducted beneath the entire central Gulf of Alaska margin.

Pavlis et al. (2004) reconstructed the western end of the collision zone over the past 3 m.y. The upper sediment unit of the Surveyor fan accumulated rapidly (Sites 178 and 887; Fig. 3), overtopping low points in the Kodiak-Bowie ridge and extending distal-fan sedimentation to the Patton-Murray ridge. Accretion along the margin north of Kodiak Seamount was probably enhanced from an abundance of trench sediment (von Huene et al., 1979, 1998; Gutscher et al., 1998). The head of the Zodiak fan and its gateway entered the trench southwest of Chirikof Island (Fig. 1).

To a first-order approximation, the reconstruction of a YT coupled with the Pacific plate represents events consistent with regional geologic history. It is recognized, however, that deformation occurred locally along the Transition fault and that the YT deforms internally. The YT basement was thrust faulted as it subducted at the Pamplona zone and in the Chugach–St. Elias fault zone (Worthington et al., 2008; Wallace, 2008). If the entire contraction of the YT were known and included, the reconstructed collision of the YT would have been earlier than shown.

INTERPRETING GEOLOGY RELATIVE TO EARTHQUAKE RUPTURE FROM MORPHOLOGY OF THE CONTINENTAL SLOPE AND SEISMIC SECTIONS

An indicator of recently subducted lower plate character is the corresponding continental slope seafloor morphology. The trace left by subducting relief is parallel to the convergence vector and transverse to trench parallel structure. Seafloor relief at least 1 km high can leave a furrow that may last for ~1 m.y., depending on the character of the continental slope (von Huene, 2008). Such traces across the Alaska margin have been imaged only since patches of multibeam bathymetry landward of the frontal prism were acquired. Plate reconstruction indicates subduction along the Alaska Trench of the YT, the 58° fracture and Aja Fracture Zone, the Kodiak-Bowie and Patton-Murray Seamount chains, and both the Surveyor and Zodiak fans during the past 10 m.y. (Fig. 2). These types of subducted features could organize earthquake rupture.

Deeply subducted seamounts can become earthquake asperities and barriers, as shown by aftershock distribution (cf. Bilek et al., 2003; DeShon et al., 2003; Husen et al., 2002; Kodaira et al., 2000; Das and Watts, 2009; Watts et al., 2010). Seamount subduction is well illustrated, for example across the Costa Rican margin, and has been described more fully elsewhere (von Huene, 2008; Watts et al., 2010).

The following discussion begins with the 1964 Alaska rupture, followed by the 1938 Semidi and the 1946 Unimak rupture areas (Fig. 1). The 1964 Alaska earthquake rupture began at a Prince William Sound asperity and then triggered the Kodiak asperities (cf. Christensen and Beck, 1994). In 1964, aftershocks extended ~660 km along the Kodiak margin from Middleton to the Trinity Islands (Fig. 1). The locations of the Kodiak asperities were derived from joint inversion of tsunami and coseismic deformation (Johnson et al., 1996; Ichinose et al., 2007). These studies indicated an asperity located oppo-

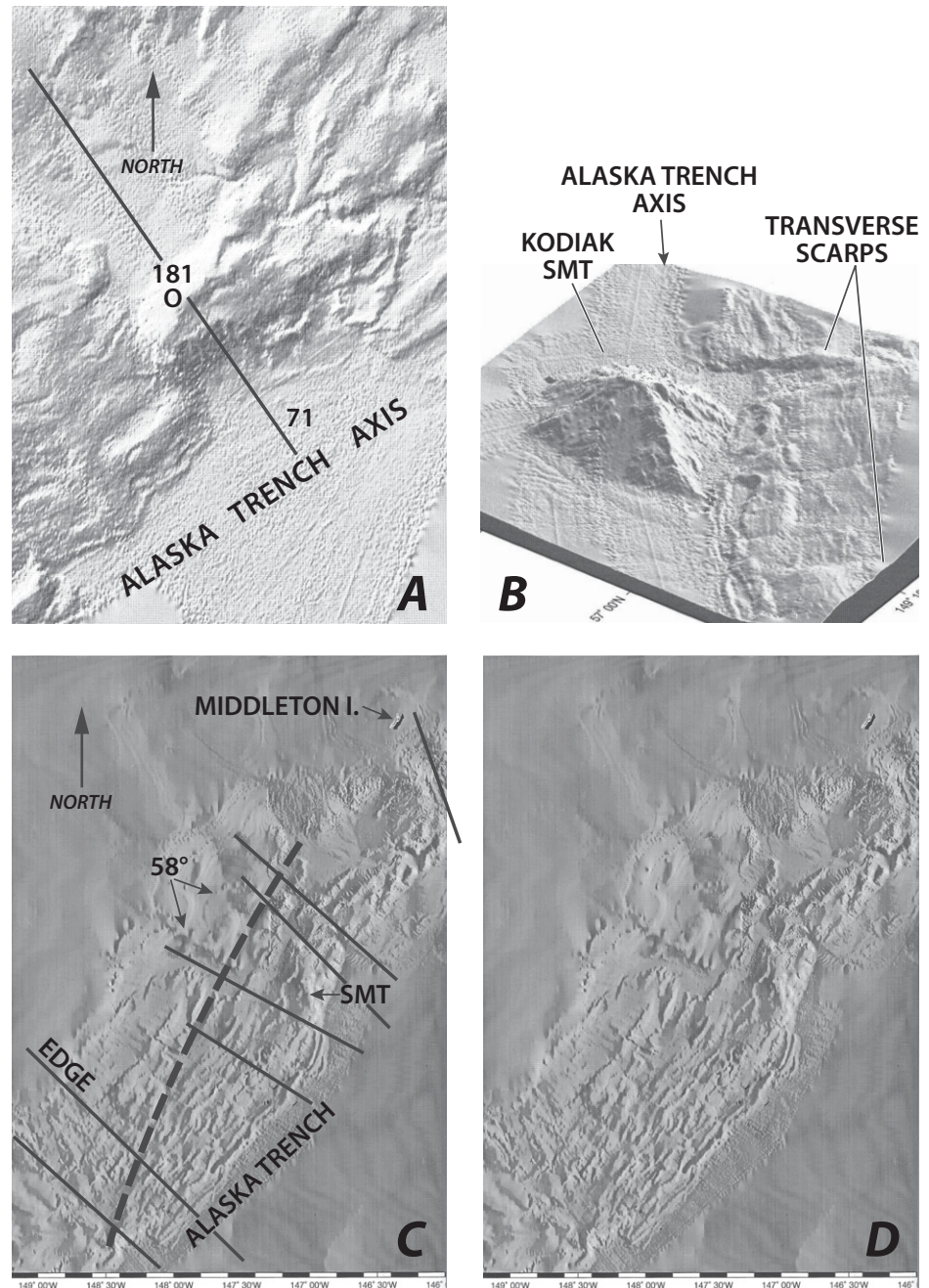
site Kodiak Seamount. The 80–150-km-wide basement ridge from which Kodiak Seamount rises (Fig. 4B) is a major morphologic feature. Landward of Kodiak Seamount, a transverse track is imaged from the deformation front to the middle slope, where multibeam bathymetric coverage ends. On the Kodiak shelf, the central shelf uplift and the Dangerous Cape High are aligned with the Kodiak-Bowie basement ridge (Fisher and von Huene, 1980). Onshore are 4 terraces locally uplifted 3–5 times more rapidly than terraces at other parts of Kodiak Island (Carver et al., 2008). The elevated trend above

the subducted Kodiak-Bowie ridge is collocated with the 1964 Kodiak asperity proposed from modeling (Johnson et al., 1996; Ichinose et al., 2007). These aligned upper plate shelf and slope features above the inferred lower plate ridge and seamounts form a transverse tectonic divide.

Kodiak North Segment

Northeast of Kodiak Seamount, the frontal prism accretes 1-km-thick trench turbidites and the underlying lower plate basement is capped by Surveyor fan sediment that subducts (Fig. 2).

Figure 4. Subducting seamounts (SMT) and slope morphology south of Middleton Island (locations in Fig. 1). (A) Alaska Trench 90 km northeast of Kodiak Seamount showing an embayment in the deformation front and truncation of the frontal prism by a subducting seamount. The slope rises abruptly 2 km over the seamount trailing flank. At DSDP Site 181, Leg 18, highly deformed sediment began 169 m subsurface above the seamount. The image in seismic line 71 (Fig. 5B) across the subducted seamount is obscured by three-dimensional complexity. (B) Kodiak Seamount (SMT) in the axis of the Alaska Trench viewed looking southwest. This seamount rises 2900 m above the trench seafloor and continues at least 1 km into the subsurface. Transverse scarps in the adjacent slope are from previously subducted ocean floor relief. (C) Annotated shaded relief of a 220-km-long segment of the Alaska margin south of Middleton Island (I.). Dashed line marks a truncated middle slope section against which a frontal prism accretes, shown in Figure 5A. Transverse gullies on the upper slope stop or deviate at the middle slope truncation. Unmarked lines indicate seismic images (Fruehn et al., 1999). One of the subducting seamounts (SMT) along the 58° fracture has clear magnetic anomaly expression. (D) As in C, but unmarked.



von Huene et al.

In the fan, an upper and lower sequence is divided by differing rates of deposition. Deposition began ca. 20 Ma in the low between YT and the Kodiak-Bowie ridge (Fig. 3), and ca. 3 Ma rates of sedimentation increased greatly. At DSDP Site 178, the upper fan section of Pleistocene age (3 Ma) is 300 m thick and the lower section of Early to Late Miocene age (19–24 to 3 Ma) is ~400 m thick. The sedimentation increase, from an average of 30 m/m.y. to 70–80 m/m.y., is consistent with an increase in the rates of coastal mountain uplift. Underlying lower fan deposits are pelagic and abyssal plain sediments on Eocene–Oligocene igneous basement. At the northeast Alaska Trench deformation front, a 1-km-thick Surveyor fan section subducts and the overlying trench fill is accreted. The subducted sediment is imaged to 40 km landward of the trench axis in 4 seismic lines (Fig. 4) (von Huene et al., 1998; Fruehn et al., 1999).

The Surveyor fan covers the 58° fracture zone and its seamounts. Magnetic anomaly maps indicate a fractured zone from 20 to 35 km wide and offset laterally 60 km (Schwab et al., 1980; Atwater, 1989; Ranero and Hoffmann, 1994). Magnetic anomalies associated with the 58° fracture extend from the central Gulf of Alaska into the subduction zone and are observed to the shelf edge. Here, it is collocated with the M2 asperity of Ichinose et al. (2007). In the ocean basin, seamounts along the fracture zone are partially buried by Surveyor fan sediment, and one disrupts the deformation front (Fig. 4C). A faint morphologic lineament across the ocean basin and an upper slope scarp parallel the magnetic anomaly offset. The sharp transverse scarp across the middle and upper slope seamount probably indicate where relief on the plate has subducted (Fig. 4C).

In the margin segment south from YT to 70 km north of Kodiak Seamount, a 250-km-long contact between the middle and frontal prisms forms a discontinuity in multibeam bathymetry (Figs. 4C, 4D). Multiple ridges are disrupted along the contact. Canyons across older terrain of the upper and middle slope also end or change there. The Miocene sediment section on the shelf can be followed downslope to within 12 km of the contact, beyond which coherent strata are no longer imaged. In the EDGE (a short-lived industry-academic group that had one major data acquisition project) image (Fig. 5), and northeast to Middleton Island, the contact separates seaward-dipping reflections in the middle prism from landward-dipping reflections in the frontal prism (Figs. 4C, 4D) (Fruehn et al., 1999). Along the EDGE transect the frontal prism has been section balanced and its shortening could have occurred in <1 m.y. (von Huene et al., 1998). The slope con-

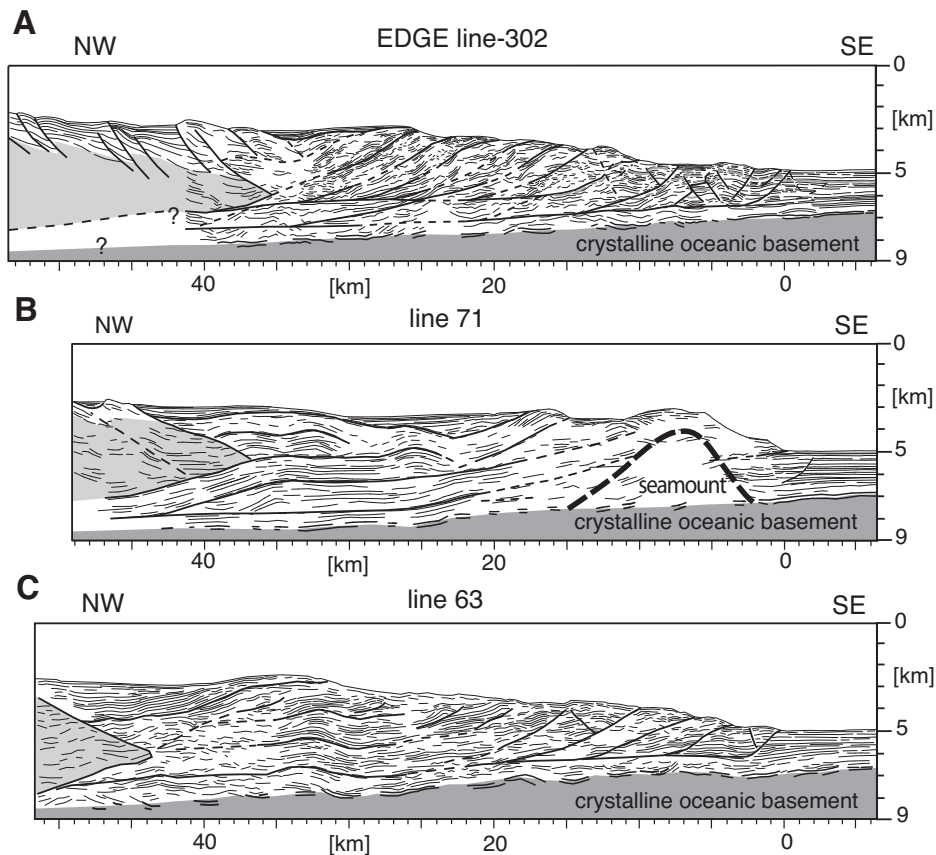


Figure 5. Line drawings of prestack depth-migrated seismic images in the northeast part of the Kodiak segment with no vertical exaggeration (location in Fig. 1). Section A is the EDGE line (von Huene et al., 1998); the light shaded area shows area of landward-vergent structure typical of the margin segment northward to the Yakutat terrane (YT). Section B shows the subducted seamount (Fig. 4A) approximated with the dashed line. Dark lines represent faults, lighter short lines are reflections from strata. Framework rock indicated by light shading has an acoustic velocity >4 km/s. Dark shading below the plate interface represents lower plate crystalline basement. Section C shows structure typical of the images in the margin segment toward Kodiak Seamount (after Gutscher and Peacock, 2003).

tains Eocene and older rocks that extend close to a Quaternary frontal prism, indicating that considerable material is missing.

The landward side of the contact is explained as the escarpment that was left after erosion during subduction of the YT, erosion that removed a previous lower slope now rebuilt by a new frontal prism (von Huene et al., 1998). The height of the YT flank is unknown but, in a refraction seismic image across the central Gulf of Alaska margin, normal oceanic crust is juxtaposed against 25-km-thick YT crust (Christeson et al., 2010). This step is bordered by a 3.5-km-deep trough and on the landward side by an ~5-km-high basement ridge. A similar structure is a permissible reinterpretation of seismic refraction data near Middleton Island (Brocher et al., 1994; T.M. Brocher, 2011, personal commun.). Models of the slope magnetic anomaly indicate

similar structures (Bruns, 1984). As this high-relief trailing edge subducts, the overlying slope fails, leaving slide scars on the slope (von Huene et al., 1999). The frontal prism contact probably formed as the trailing edge of the YT ended its erosional phase and began subducting. At the contact between the middle and frontal prism in the EDGE line, the upper plate is ~4 km thick (Fig. 5). Subducting seamounts off Costa Rica that are 2–2.5 km high erode the lower slope wedge of the upper plate until it is ~4 km thick before tunneling into the margin. Once frontal erosion by slope failure no longer overwhelms tectonics, the scarp becomes an interface against which erosional debris and trench sediment accrete to rebuild a frontal prism. Plate tectonic reconstruction (Fig. 2) shows the YT trailing flank migrating 200 km along the diagonal track in the past 4 m.y. The purpose of this longer

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explanation is to correct the often-cited explanation of Seely (1977) and Dickinson and Seely (1979) that obducted trench sediment in this margin segment indicates accretion along the entire Kodiak margin slope; their interpretation of seaward-dipping thrust faults is correct, but rather than being constructed of obducted trench sediment, the slope landward of the frontal prism contains faulted continental framework rock and its Cenozoic sediment cover. The seaward-dipping thrust faults probably formed during YT collision.

Southwest of the seamount at the diagonal contact end (Figs. 4A, 4C), and toward Kodiak Seamount, the margin lower slope is a 40-km-wide accreted frontal prism. Uniformly thick (1–1.5 km) thrust layers >20 km long are imaged (Fig. 5) (Gutscher et al., 1998). It is proposed that these thrust layers are composed of Surveyor fan sediment accreted in two or three exceptionally long sheets separated by décollements. Such thrust sheets may have been sourced from the trough of thick sediment along the YT trailing flank. As the YT trailing flank migrated past this area, the thick Surveyor fan may have been unable to subduct and it accreted, as it does currently along the EDGE line (Fig. 5A).

Where the diagonal contact intersects the trench, a subducted seamount at the front of the margin was drilled at DSDP Site 181 (Fig. 4A). Shallow sediment on the seamount is no older than 1 Ma, and below 169 m depth it is highly deformed, dewatered, and overconsolidated much more than is normal at the depth from which it was recovered (Lee et al., 1973). The highly compacted and deformed sediment on the seamount indicates an elevated level of friction over subducting relief, as would be expected at an earthquake asperity (Fig. 4).

Kodiak South Segment

The southwest limit of 1964 earthquake rupture is collocated with the intersection of Patton-Murray ridge and the trench axis (Fig. 1). Between Kodiak Seamount and Patton-Murray ridge, the continental slope is steep and narrow relative to north of Kodiak Seamount (Fig. 1). The top of the upper slope from the Trinity Islands to Chirikof Island is indented by two embayments not headed by glacial troughs. These might indicate old tracks of subducting relief. Opposite the Trinity Islands a short segment of multibeam bathymetry (Fig. 6) ties together several seismic lines (Miller and von Huene, 1987), one of which was depth migrated (Fig. 7).

In a multibeam bathymetry perspective from the shelf to the trench axis (Fig. 6), a break in slope occurs at the base of continental frame-

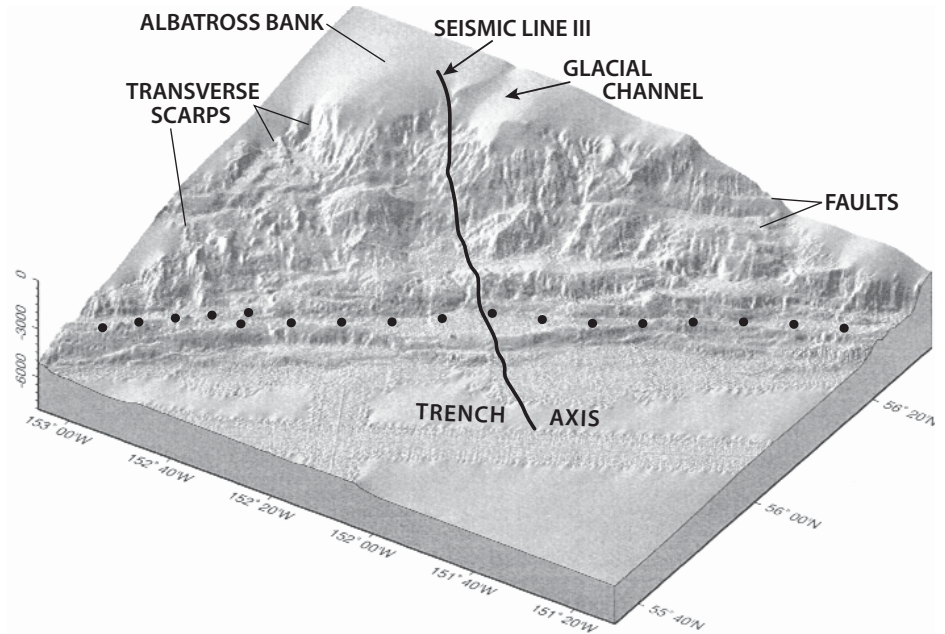


Figure 6. Shaded relief perspective from a multibeam bathymetric survey (acquired with *Forschungsschiff Sonne* in 1994) of the continental slope at the southwest end of the Kodiak segment, the Albatross Bank area (location in Fig. 1). The image extends from the trench to the shelf edge, where detail ends. Morphology of the frontal prism (seaward of dotted line) contrasts with that of the more mature middle to upper slopes. Between them is a complex structural zone covered by slide debris, which could not be imaged well, that forms a transitional segment. The location of seismic line 111 (Fig. 7) is indicated by the heavy line. Faults in eight other seismic lines, evident in the slope morphology, are connected in the multibeam data. The spillway of a glacial channel across the shelf enhanced erosion of the centered embayment across the slope.

work rock. The steep rugged upper and middle slopes end at a smoother and shallower dipping lower slope frontal prism, indicating a break in geology. Transverse canyons and the central embayment terminate at the frontal prism. One of several seismic transects extends down the embayment (Fig. 7). Mid-slope faults in seismic images that were interpreted with reservations became clear in morphology acquired 13 years later (Flueh et al., 1994). In 6 depth converted seismic images, the Miocene shelf sediment section can be followed down slope into the upper to middle slope transition where water depths are 2–3 km (von Huene et al., 1986). The underlying margin framework rock probably extends to the lower break from a steep to a shallower slope. In a nearby industry line tied to the KSSD3 COST (Continental Offshore Stratigraphic Test) drill hole on the shelf (Turner et al., 1987), the Eocene and Miocene sections extend to the end of the line on the upper slope where the Eocene sediment section is >1 km thick (Winston, 1983). On land, Eocene units overlie Cretaceous rock. The upper and middle slopes of more competent older rock that form

the steep slopes extend close to a frontal prism of much younger sediment. The frontal prism sediment volume could have accreted in <1 m.y., assuming convergence of present trench sediment thicknesses. Material missing between the margin framework rocks and the probable Quaternary frontal prism indicates a period of tectonic erosion.

Beneath the frontal prism on the lower plate (Fig. 7), subducting fan and trench sediment are imaged 40 km down the subduction zone. Inferring the full extent of the thick subducted sediment is problematic because the age of the current accreting frontal prism, which marks the time when subduction of erosional material ended, can only be approximated.

The Patton-Murray Seamounts rise from a ridge that is clearly evident in satellite gravity data (Andersen et al., 2005). Where this ridge subducts, the Alaska Trench axial gradient decreases and sediment fill is thinner. Only large-scale features are resolved in bathymetric maps of this ridge and associated fracture zones, as indicated by uncharted seamounts in long range sidescan sonar (GLORIA; geological

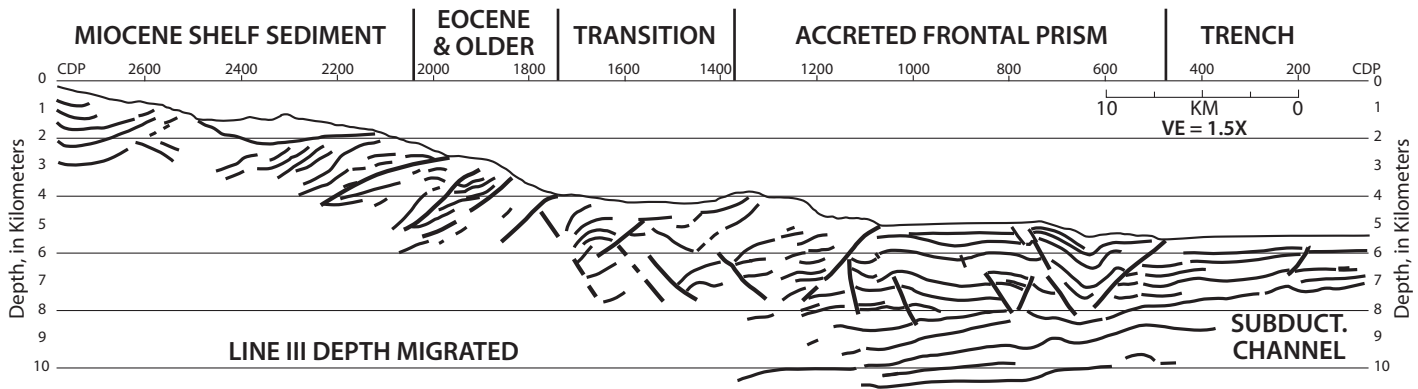


Figure 7. Line 111, a depth-migrated seismic image in line drawing (CDP—common depth point; VE—vertical exaggeration). The subduction channel beneath the frontal prism contains Surveyor fan sediment. The left end of the line is at Albatross Bank where drilling recovered the thick Eocene section that is unconformably overlain by Miocene sediment. The Miocene section continues downslope to ~2 km water depth in this image and even farther in neighboring seismic images, indicating the seaward extent of the continental framework. Across the transition between framework rock and the frontal prism, the Eocene to Quaternary section is probably missing.

long range inclined asdic) images (Ryan et al., 1988). The Aja Fracture Zone displaces magnetic anomalies for 165 km, indicating a major crustal structure (Atwater, 1989). In satellite gravity and bathymetric maps, two parallel lineaments are apparent. South of the main lineament a shorter one cuts across the western end of the Patton-Murray ridge, leaving a line of small seamounts (Fig. 1). The Aja Fracture Zone crosses the trench and extends up the continental slope between the Trinity Islands and Chirikof Island (Maus et al., 2009). The 1938 and 1964 aftershock areas end along the subducted trend of the Patton-Murray ridge and fracture zones.

Semidi Islands Segment Between Chirikof and Shumagin Islands

Earthquake rupture of the Semidi Islands area in July of 1788 sourced a tsunami 3–10 m high on Kodiak Island, as mentioned in a Russian account (E.A. Okal, 2009, written commun.). The 1938 Semidi Islands aftershock area (Fig. 1) marks an earthquake that was felt from Unimak Island to Anchorage, and its modest tsunami was recorded in the Aleutian Islands, Hawaii, and California. Aftershocks were relocated many years later (Estabrook et al., 1994; E.A. Okal, 2009, written commun.). Sykes (1971) proposed that the southwest end of the 1938 aftershocks is at the Shumagin gap because the last major earthquake there was in 1903. Several modest earthquakes including the 1993 M 6.9 event have occurred in the gap, but on the basis of geodesy, it appears to accumulate little strain (Lisowski et al., 1988; Savage et al., 1986; Freymueller and Bevan, 1999). From modeling of the subduction zone, however, the area is con-

sidered capable of nucleating a large earthquake in the future (Zheng et al., 1996).

The subducting plate abreast of the 1938 aftershock zone has only low mounds in conventional bathymetry, probably because relief is covered by Zodiak fan sediment as much as 600 m thick and by 250 m of pelagic sediment (Stevenson and Embley, 1987). The fan formed in Late Eocene to Early Oligocene time from a North American terrigenous source. As mentioned previously, the single sediment gateway during 10 m.y. is now subducted. If fan channels are projected northward into the subduction zone they converge at the inferred extension of the Patton-Murray or Kodiak-Bowie ridges. The inferred fan head entered the trench ca. 3 Ma (Fig. 2). The 1938 aftershocks are collocated in the area of the subducted fan head.

The upper plate structure is similar to that of the Albatross Bank area (Figs. 6 and 7), with a frontal prism, a transition zone of poorly imaged structure, and a relatively steep middle slope (Fig. 8). Frontal prism volume could have accreted in <1.25 m.y. An Eocene to Quaternary section on the shelf can be followed continuously to the base of the middle slope (Bruns et al., 1987). The missing rock between the margin framework and frontal prism again indicates a period of erosion. Early multibeam bathymetry imaged the accreted frontal prism morphology along the lower and part of the middle slope (Lewis et al., 1988). In 1994 a block of multibeam bathymetry across the lower and middle slope, acquired with a more advanced instrument system, provided better resolution (Fig. 8). A seismic image across that block (Fig. 8) shows that fan sediment subducts and the pelagic cover accretes into the frontal prism. The Zodiak fan forms the top of the sub-

duction channel (Fig. 8) and the upper plate basement is exposed in the Shumagin Islands (Bruns et al., 1987), where metamorphosed turbidites of Cretaceous age intruded by Paleocene granodiorite crop out.

Shumagin Islands to Unimak Pass Segment

In this segment, the shelf and upper slope retain structures formed during the pre-Aleutian arc period, a time when the Alaskan margin curved from its southwest trend to a northwest one and continued as the Bering margin (Bruns et al., 1987; Scholl et al., 1987). Dominant tectonic features cross the shelf and upper slope diagonally parallel to the Beringian margin. They have been overprinted on the slope by the Neogene Alaska Trench and Aleutian Trench regional trend, which probably obscured or destroyed the hinge between the Alaska and Beringian structures. The area is also one of variable subduction zone dip (Hayes et al., 2009). These structures appear sufficiently profound to influence segmentation of great earthquake rupture.

The Unimak to Shumagin Islands area was shaken by a destructive M 8.3 tsunami earthquake in 1946 (Lopez and Okal, 2006). Aftershocks were concentrated across the slope between Sanak Basin and Unimak Basin (Fig. 9). At Scotch Cap on Unimak Island, earthquake shaking did only minor damage, but the associated tsunami destroyed the lighthouse and U.S. Coast Guard buildings with a wave 42 m high. At Hilo, Hawaii, the wave was 16.8 m above sea level and took 159 lives, causing 26 million U.S. dollars in property damage. This tsunami also damaged buildings in the Aleutian and South Pacific islands (Fryer and Tryon, 2005). The

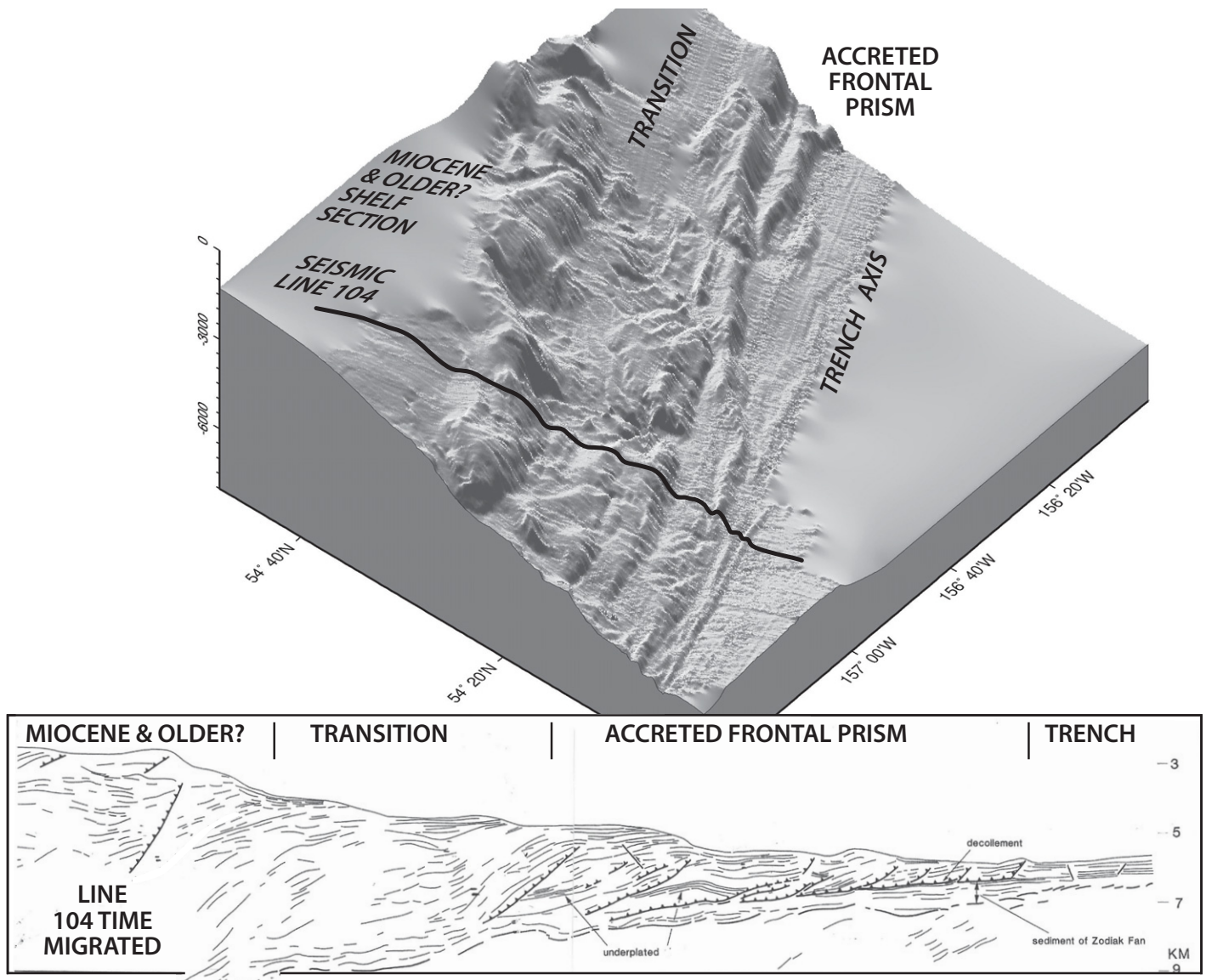


Figure 8. A section across the 1938 Semidi Islands earthquake margin (location in Fig. 1). Top is a perspective diagram extending from the trench axis only to the middle slope. Heavy line indicates the location of seismic image 104 below. Ridges along the lower slope are fault-bend folds of the frontal prism that merge into a transitional segment. Steep slopes indicate more competent older rock than that of the frontal prism. The pre-stack time migrated seismic line is converted to depth with sonobuoy refraction velocities (Bruns et al., 1987). In this seismic image, the Miocene shelf stratigraphy extends to within 6–10 km of the accreted frontal prism. Area balancing indicates that the frontal prism could form in ~1.25 m.y. under present conditions.

large tsunami runup at Scotch Cap is explained with a slide during the earthquake (Lopez and Okal, 2006; Okal and Synolakis, 2004; Fryer et al., 2004). However, despite two subsequent surveys of morphology in the possible slide area, the causative slope failure is not yet unmistakably identified (Fryer and Tryon, 2005).

On the subducting ocean crust, the most prominent relief in conventional bathymetry is a southward-trending line of four seamounts (two contained in Fig. 1). Small areas of multi-beam bathymetry show minor relief not imaged

in conventional bathymetry scattered across the seafloor. Ocean basin sediment, ~500–800 m thick, is subducted along with trench axis sediment <1 km thick.

The shelf and slope between the Shumagin Islands and Unimak Pass contains a morphologic transition from an Alaskan to an Aleutian margin (Figs. 1 and 9). The most obvious morphologic change is the appearance of an Aleutian mid-slope terrace. In the transitional segment, Unimak Seamount and Unimak ridge dominate the middle slope (Fig. 9). The sea-

mount exposes an arc igneous basement from which shallow-water Eocene to late Pliocene sedimentary rocks were dredged (Bruns et al., 1987). Unimak ridge is bounded on either flank by extensional structures imaged with seismic data processed at a basic level (Bruns et al., 1987; Lewis et al., 1988). The ridge forms the seaward flank of an upper slope basin containing Late Miocene to Quaternary sediment.

The Shumagin Islands expose the top of a broad basement ridge that is separated from a similar Sanak Island basement ridge by the

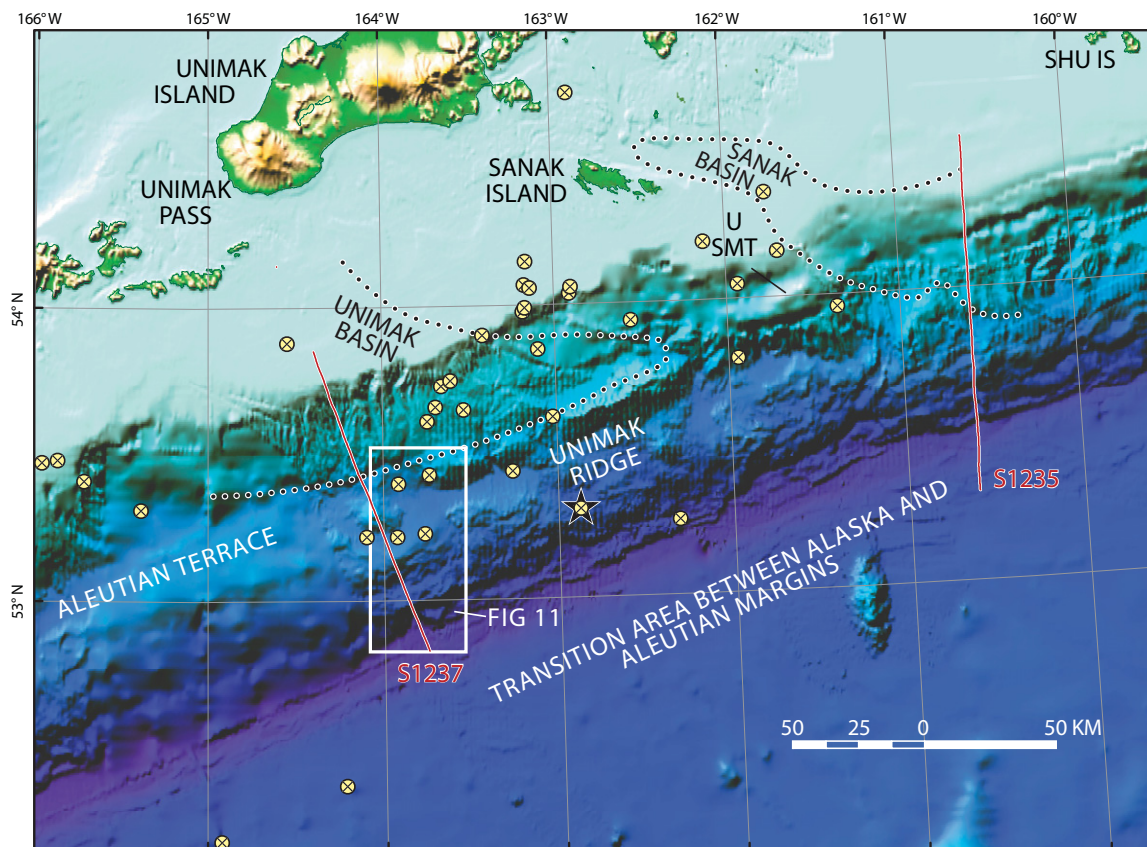


Figure 9. Bathymetry between Shumagin Islands and Unimak Pass. Seismic lines acquired by RV *Ewing* (Fig. 10) and the 2 km contour of shelf basins (modified from Bruns et al., 1987) are indicated by dotted lines. Circles are 1946 aftershocks (from Lopez and Okal, 2006). The earthquake was located in the Aleutian segment and ruptured only to Sanak Basin. U SMT—Unimak Seamount; SHU IS—Shumagin Islands. Area of Figure 11 and *Ewing* seismic lines S1235 and S1237 are indicated.

intervening 7-km-deep Unimak Basin (Bruns et al., 1987) (Fig. 9). Opposite the Shumagin Islands basement, the trench axis narrows because of a broad seaward bulge. Similarly, on the middle slope, Unimak Seamount forms the end of the Sanak Island shallow basement. Flanking Sanak Island basement to the north, the long and narrow Sanak Basin cuts diagonally across the shelf. The southwest flank of the Shumagin basement mass was imaged in seismic line 1235 (Figs. 9 and 10A), which also imaged the eastern Sanak Basin. Aftershocks during the first 19 days following the 1946 earthquake stop at Sanak Basin and the area they outline is relatively small for its magnitude.

A second seismic line (1237; Figs. 9 and 10B) through Unimak Pass to the trench axis is located immediately southwest of the main 1946 aftershock activity. The sediment filling Unimak Basin on the shelf is imaged downslope and continues beneath the Aleutian terrace. The sedimentary sequence is cut by many landward-dipping normal growth faults with 100–200 m

vertical displacement in a so-called bookshelf pattern. Downward bending as the continental slope subsided could produce that fault pattern. A major fault zone forms the landward boundary of the Aleutian terrace, and seaward the Unimak Basin sediment sequence is truncated only 25 km from the trench axis. At the foot of the slope, the seismic image crosses a characteristic reentrant formed by a subducted seamount (Fig. 11); a 1.5-km-high feature imaged ~7 km down the subduction zone is likely to be the seamount. Reflections in the accreted frontal prism are disorganized consistent with disruption by seamount subduction. The entire 1-km-thick trench sediment section subducts (Fig. 10).

Across the upper and middle slope, multi-beam bathymetry contains many morphological features left by past slope failure. The seismic image contains truncated beds from upper slope failure and slumped masses downslope (Fig. 10). This area appears prone to sliding that probably resulted from steepening during erosion at the base of the upper plate and slope subsidence.

DISCUSSION

Finding a relation between geology in subduction zones and historical earthquakes can indicate where future great earthquakes along the Alaska margin are likely to occur. Spatial collocation of the 1964 Alaska earthquake's Kodiak asperity and both the Kodiak-Bowie Seamount chain and the 58° fracture was observed (cf. Johnson et al., 1996; Ichinose et al., 2007). Here we expand the observations of this relation. Three large features extend into the Alaska subduction zone and are collocated with 1964 aftershock areas, namely the YT, and the Kodiak-Bowie and Patton-Murray ridges, and associated seamounts. The Prince William and Kodiak asperities are separated by the abrupt increase in crustal thickness of the YT (Brocher et al., 1994; Christeson et al., 2010). West of Middleton Island, this boundary is observed deep into the subduction zone as a continuation of the slope magnetic anomaly (i.e., Schwab et al., 1980). The magnetic

Alaska margin geology

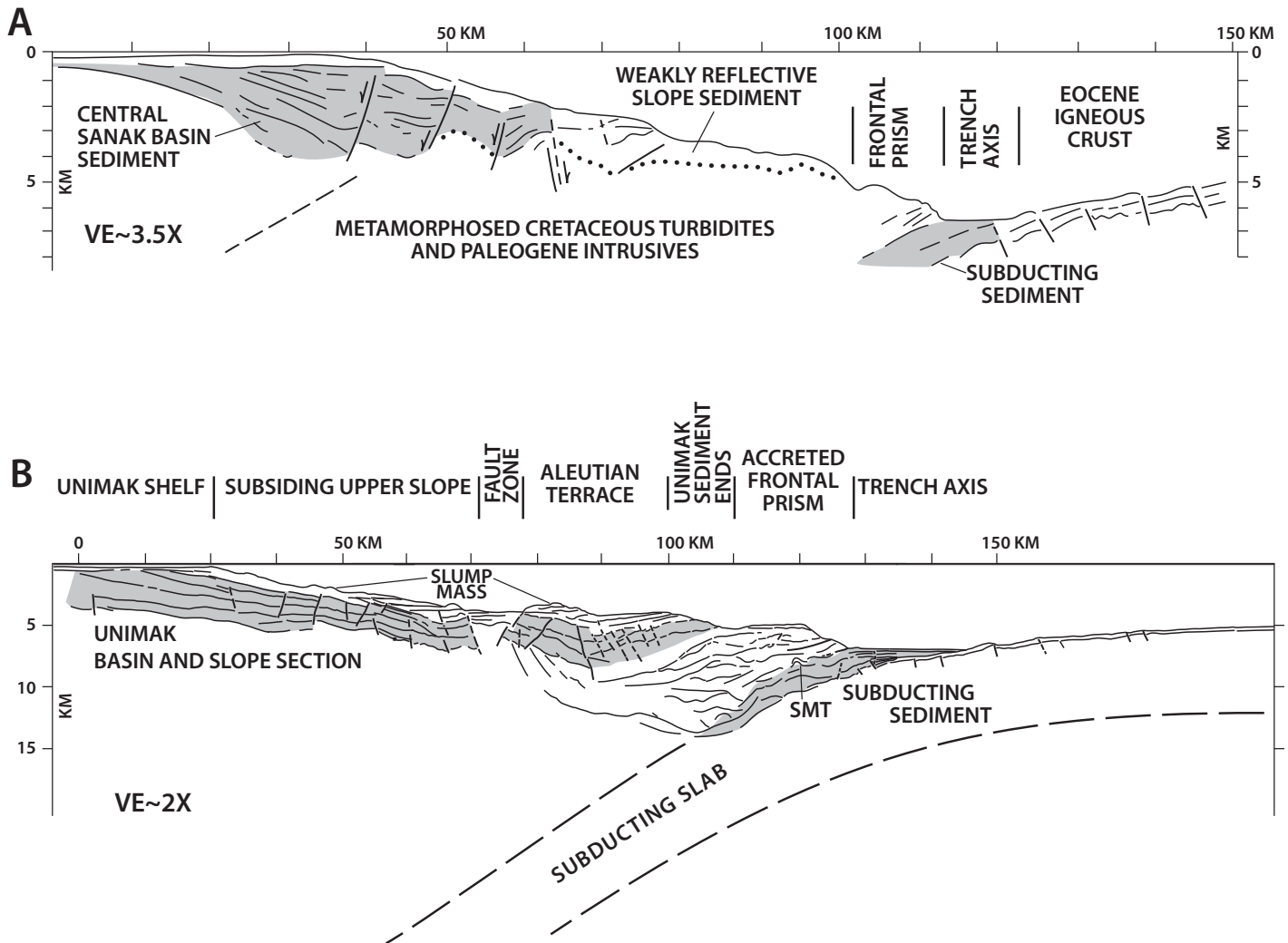


Figure 10. Depth-migrated seismic data acquired with RV *Ewing* in 1994 shown as line drawings (VE—vertical exaggeration). (A) Line 1235, from the Shumagin Islands across the seaward end of Sanak Basin and the southern end of the Shumagin shallow basement. Deep landward-dipping dashed line is the inferred landward side of the basement, consisting of Paleocene granodiorite that intruded Cretaceous metamorphosed turbidites, exposed on Shumagin Islands and Sanak Island. Landward of this line the basement could be arc volcanic rock like that dredged from Unimak Seamount. (B) The Unimak Basin sediment section (shaded area) can be followed to the Aleutian terrace, where structure in an extensional tectonic zone is not resolved, requiring a correlation based on seismic character. Many normal faults (vertical to subvertical lines) with 200 m or less vertical displacement cut the shelf section. Slope apron strata, not shaded, are largely composed of slide debris. At its seaward edge the terrace was uplifted and truncated during tectonic thickening of the underlying thrust faulted mass. The frontal prism structure was probably disturbed from subduction of an ~1-km-high seamount (SMT). The subduction channel has accommodated the entire trench axis fill (shaded).

anomaly trend is collocated with an alignment of east-west-trending upper plate structures between the two main 1964 asperities, including the Amatuli Trough (Fig. 1), Augustine-Seldovia arch (Fisher et al., 1987), and the volcanic arc offset near Augustine volcano. The trend corresponds with a change in the pattern of microseismicity (Eberhart-Phillips et al., 2006) and a geodetic reversal in direction of upper plate movement (Frey Mueller et al., 2008). With a feature of this extent and magni-

tude, it is not surprising that it divided the 1964 earthquake asperities and their rupture areas.

At the southwest end of the 1964 aftershock area is the subducted Patton-Murray ridge and the Aja Fracture Zone (Fig. 1). Although only a small part of the slope affected by the collision has been mapped geophysically, the available seismic and multibeam coverage reveals transverse scars across the slope that offset presumed glacial deposits. In a seismic line striking across the middle slope (not shown herein), the

transverse scars correlate with stratal disruption (Miller and von Huene, 1987) so subsurface observations are consistent with subduction of lower plate relief beneath the continental margin. This area of multiple collisions warrants a more extensive survey with high-resolution multibeam systems to learn more about earthquake rupture barriers.

Bracketed between the Patton-Murray ridge and the YT is the Kodiak-Bowie ridge and associated seamounts. Its collision with the Kodiak

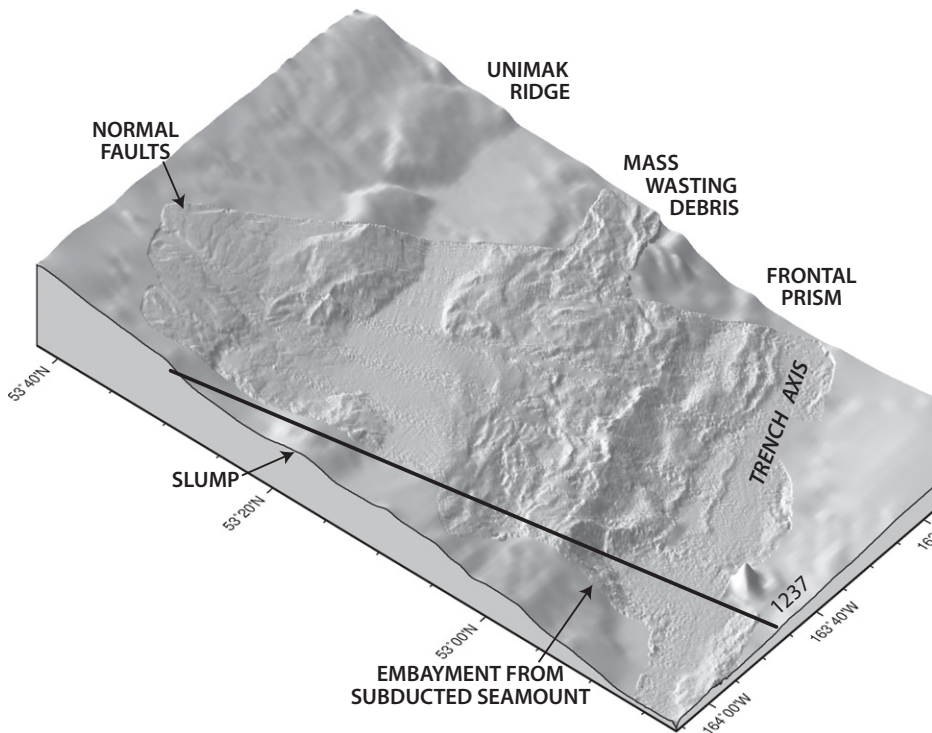


Figure 11. Multibeam bathymetry of a middle and lower slope area opposite Unimak Pass shown in perspective and set into surrounding conventional bathymetry (location in Fig. 1); it crosses the eastern end of the Aleutian terrace. The seismic image of Figure 10B crosses the western edge of the multibeam perspective and the reentrant from seamount subduction at the base of the slope. Half of the seamount approaching the margin was imaged and the other half was interpolated, giving it the smooth pointed shape. (Multibeam bathymetry was acquired by Forschungsschiff *Sonne* in 1994.)

margin is documented with limited multibeam data on the lower slope (Fig. 4B) and with local uplifted terraces on land. Uplift across the shelf seafloor is not clear in conventional bathymetry, but two main glacial channels extended across the shelf and were deflected on either side of a broad morphological high (von Huene et al., 1980) aligned with the Narrow Cape sequence of uplifted terraces onshore (Carver et al., 2008). Lower plate relief in the subduction zone is collocated with the 1964 Kodiak asperity and current geodetic indicators of crustal movement.

The young upper plate transverse features are collocated with subducted relief of pre-Pleistocene age. Oblique convergence along the margin imparts a 20–45 km/m.y. northward migration to east-west-trending Pacific plate structures (Fig. 2). The Albatross Bank anticline (Fig. 1) (Fisher and von Huene, 1980) first formed at the time the currently collocated Patton-Murray ridge was ~900 km away (Fig. 2), and so the current collocation is a transient happenstance. The inferred age of Tugidak Basin located in the complex upper plate structure between the Trinity Islands and Chirikof Island is also inferred to

predate arrival of the Patton-Murray ridge; therefore, the arrest of 1964 rupture in the southwest may have involved both upper and lower plate structures that formed independently. Similarly, the coincident location of the 58° fracture and the transverse Portlock Bank on the shelf may have contributed to the collocated asperity found by modeling (Ichinose et al., 2007). When both upper and lower plate discontinuities coincide, they probably reinforce the effect of geologic structure on earthquake rupture organization.

Lower plate relief and fracture zones can act as both asperities and barriers. During the 1964 earthquake, the Kodiak-Bowie ridge was an asperity whereas the Patton-Murray ridge was a barrier. Similarly, the 58° fracture was an asperity in 1964 and the Aja Fracture Zone was part of a barrier. Examples in other areas include: (1) a fracture zone subducting beneath the Peruvian margin acted as a barrier to delay rupture during a M 8.4 earthquake in 2001 (Robinson et al., 2006), and (2) lower plate relief along the Juan Fernandez ridge subducting beneath central Chile was a barrier in the 2010 earthquake but an asperity for the 1985 earthquake. Seamounts

are observed to be both barriers and asperities (Kodaira et al., 2000; Watts et al., 2010; Das and Watts, 2009; Husen et al., 2002; DeShon et al., 2003). Forming an asperity at one time and a barrier at another results from the difference in friction over relief that produces a seismic cycle different from the adjacent areas of the plate interface. The friction, and therefore the seismic cycle of the asperity or barrier, is different from that of its surroundings. The seismic cycle of the relief can be in phase or out of phase with the surrounding plate interface cycle. If out of phase, relief forms an area of low stress that is a barrier, and if in phase, it can be a triggering asperity.

The influence of material on seismogenic behavior is suggested by the Semidi Island segment between the Trinity and Shumagin Islands. The 1938 aftershock strain release is largely contained within the area of the subducted Zodiak fan (Fig. 1). The fan consists of fine-grained material that has been compacted since Eocene time. Subducted along its flanks is Neogene trench sediment that has different physical properties and thus has contrasting frictional properties. Current plate movement in the 1938 aftershock area from global positioning system information is diverse. The Chirikof and Semidi Islands move subparallel to the Pacific–North America convergence vector, whereas south of the fan the much smaller movement of the Shumagin Islands is divergent (Freymueller et al., 2008).

In the Unimak segment the continental Alaska margin transitions to Aleutian arc. The shelf inherited structure parallel to the Beringian margin that continues down the middle slope (Bruns et al., 1987) (Figs. 9 and 10). The upper and middle slope extensional fault pattern is similar to the horst and graben structure of bend faults in the subducting oceanic plate. Curvature from bending of the upper plate is not as evident as on the ocean crust, but is consistent with evidence of a 3 km subsidence of the middle slope (Bruns et al., 1987) and much less subsidence on the shelf. Erosion of the landward slope is probably much faster than seafloor erosion on the subducting plate and will therefore contribute to modification of the faulted profile of the upper plate.

The speculation that the 1946 large tsunami may have involved slope failure is not confirmed by location of a particular large and fresh slump. Confirmation requires a dedicated multibeam bathymetric survey with tens of meters of spatial resolution. The spatial relation of aftershocks to the Sanak ridge is an indicator of an upper plate feature that was a barrier to earthquake rupture propagation. The character of the exposed subducting plate appears to be without extensive relief or contrasting sediment masses.

The Alaska margin is commonly referred to as an example of steady-state constant accretion, and it exemplifies a first simple model that persisted despite being incorrect, probably because of its elegant simplicity. Seminal to this idea was the interpretation of early marine data (Stoneley, 1967; Seely, 1977) reinforced by interpretations of much older geology on land. In early unmigrated seismic records of convergent margins, landward-dipping reflections were categorically interpreted as representing accretion of trench sediment. With better seismic images, many landward-dipping reflections in early unmigrated records proved to be diffractions. The best imaged features were frontal prism structures in the relatively thin prism apex. Most margins have frontal prisms with an imbricate tectonic structure and those constructed of detached trench sediment are accretionary. Those composed of mass-wasted slope sediment do not contain material transferred from the lower plate. Accretionary structure was commonly assumed in the obscured image upslope, where not much except faint landward-dipping reflections or diffractions were depicted.

The structure studied by Stoneley (1967) is confined to the Pamplona zone that ends at Kayak Island (Worthington et al., 2010), which is structurally similar to a frontal prism. The obducted structure illustrated by Seely (1977) extends at most for ~200 km south of Middleton Island in the area presumably affected by subduction of the YT (Fruehn et al., 1999). The unsampled material in those landward-vergent thrust slices was assumed to be trench sediment. Reflectors in shelf basins, examined with COST drill samples, are clearly derived from erosion of the adjacent land, and these reflectors extend through the faulted section to the middle slope in the pre-stack depth-migrated EDGE line (Fig. 5A). The obducted section is a thrust-faulted slope sediment section and not accreted trench turbidites. We propose that the landward-verging thrusts may have formed from contractile deformation during YT collision. Seismic images where YT subduction was most recent near Middleton Island show a truncated slope structure covered by thin slope sediment (Fruehn et al., 1999). The eroded seaward end of margin framework rock subsequently backed an accreted prism.

From Kodiak Seamount to Unimak Pass, most seismic lines show the Neogene shelf section extending down the slope. Several seismic images show a structurally complex transition segment against which the frontal prism accreted (Miller and von Huene, 1987). The Alaska margin commonly consists of truncated margin framework sections that end in a steep slope against which a younger frontal prism has accreted.

The Alaska margin mixed history of erosion and accretion has implications for interpretations of material that has subducted into the seismogenic zone. When a frontal prism accretes trench sediment, the sediment thickness exceeds the capacity of the subduction channel to accept the entire sediment section. Accretionary frontal prisms are likely to have a subduction channel filled with trench sediment. If the accreted prism is backed by the eroded seaward end of the continental framework, the subduction channel is likely to have previously contained eroded debris.

Recognizing an erosional or accretionary margin is significant to understanding the material and morphology along plate interfaces. In a study of global seismology, Bilek (2010) concluded that if the Alaska margin is accretionary, its seismological record is anomalous. Accretionary margin plate interfaces are perceived as containing trench sediment and erosional ones as containing heterogeneous eroded debris. These differences in material produce physical differences (Fagereng and Sibson, 2010; Marone and Richardson, 2010) that influence interplate frictional behavior. If subducted trench sediment produces large areas of uniform friction, rupture can propagate across greater areas than if impeded by lower plate relief or heterogeneous friction along plate interfaces. A plate interface in homogeneous material may produce earthquakes at more regular intervals than those occurring in heterogeneous materials (Fagereng and Sibson, 2010). To understand material character in the Alaskan seismogenic zone, it is useful to recognize the transition from dominantly eroded lower crustal rock to subducted trench sediment.

INFERRED MATERIAL ALONG THE PLATE INTERFACE

The change from a dominantly erosional to an accretionary Alaska convergent margin came with increased trench sediment input during the past 3 m.y. Material in subduction channels is implied to influence seismic behavior (Marone and Richardson, 2010; Fagereng and Sibson, 2010). Subduction channels of accreting margins commonly contain trench and ocean-basin sediment, dominated by clay, silt, and sand. Subduction channels of eroding margins are likely to contain a relatively heterogeneous mix of sediment and hard rock from the upper plate seafloor and clasts of lower crustal material detached from the base of the upper plate. A fossil subduction channel in the Apennines, for example, contains a *mélange* of reworked blocks from the upper plate and slope sediment (Vannucchi et al., 2008). Fault zones of hetero-

geneous materials are subject to variable shear strain rates (Marone and Richardson, 2010; Fagereng and Sibson, 2010), and the seismicity of accreting and eroding margins has been observed to differ (Bilek, 2010). We infer plate interface materials from tectonic history and geology (Fig. 12).

Lower plate relief entering the subduction zone and the upper plate features that developed above them are collocated with aftershock limits and asperities. The 1964 Kodiak asperity northern rupture limit is along the YT trailing flank. Its configuration (Christeson et al., 2010) is a likely barrier to rupture runout. Erosional debris and sediment from YT collision probably entered the trench, were transported down the axis, and were deposited with trench turbidite on top of the Surveyor and Zodiak deep-sea fans (Fig. 2).

Three high-relief ocean-basin features have organized great earthquake rupture along the Alaska margin (Fig. 12). The 58° fracture is not obvious in seafloor morphology because ~900-m-thick sediments of the Surveyor fan bury it. However, it is clearly defined in magnetic anomaly maps as a major tectonic zone and is collocated with an asperity during 1964 that may have slipped 14 m (Ichinose et al., 2007). To the south, the Kodiak-Bowie ridge asperity also slipped 14 m. A subducted continuation of the Patton-Murray ridge and the Aja Fracture Zone divides the 1964 and 1938 ruptures.

Tectonic and geologic history provides an insight into subducted materials that are collocated with aftershock areas (Fig. 12). The 1938 Semidi Islands rupture area is dominated by the Zodiak fan. Its M 8.2 main shock and aftershocks (E.A. Okal, 2009, written commun.) occur near the subducted Zodiak fan head. A lower plate physical barrier that may have stopped this rupture to the southwest is not obvious in the scanty data here, but it could be a basement mass that supports the Shumagin Islands. Currently, a great deal of trench axial sediment bypasses this area because of its steepened axial gradient. Only the ~400-m-thick trench sediment accretes into the frontal prism (Fig. 8), and the underlying Zodiak fan section subducts. This division may result from the difference in physical properties.

Surveyor fan sediment, however, may not have reached the capacity of the subduction zone to accept sediment prior to 3 Ma. The Alaska subduction zone northeast of Kodiak Seamount accommodates a ~1 km thickness of sediment. The lower Surveyor fan section, if gauged by sediment at Site 178, may have been only 150 m thick at 10 Ma, and prior to 3 Ma the fan section was 500 m thick. Trench sediment accretion along the northeastern Kodiak margin was

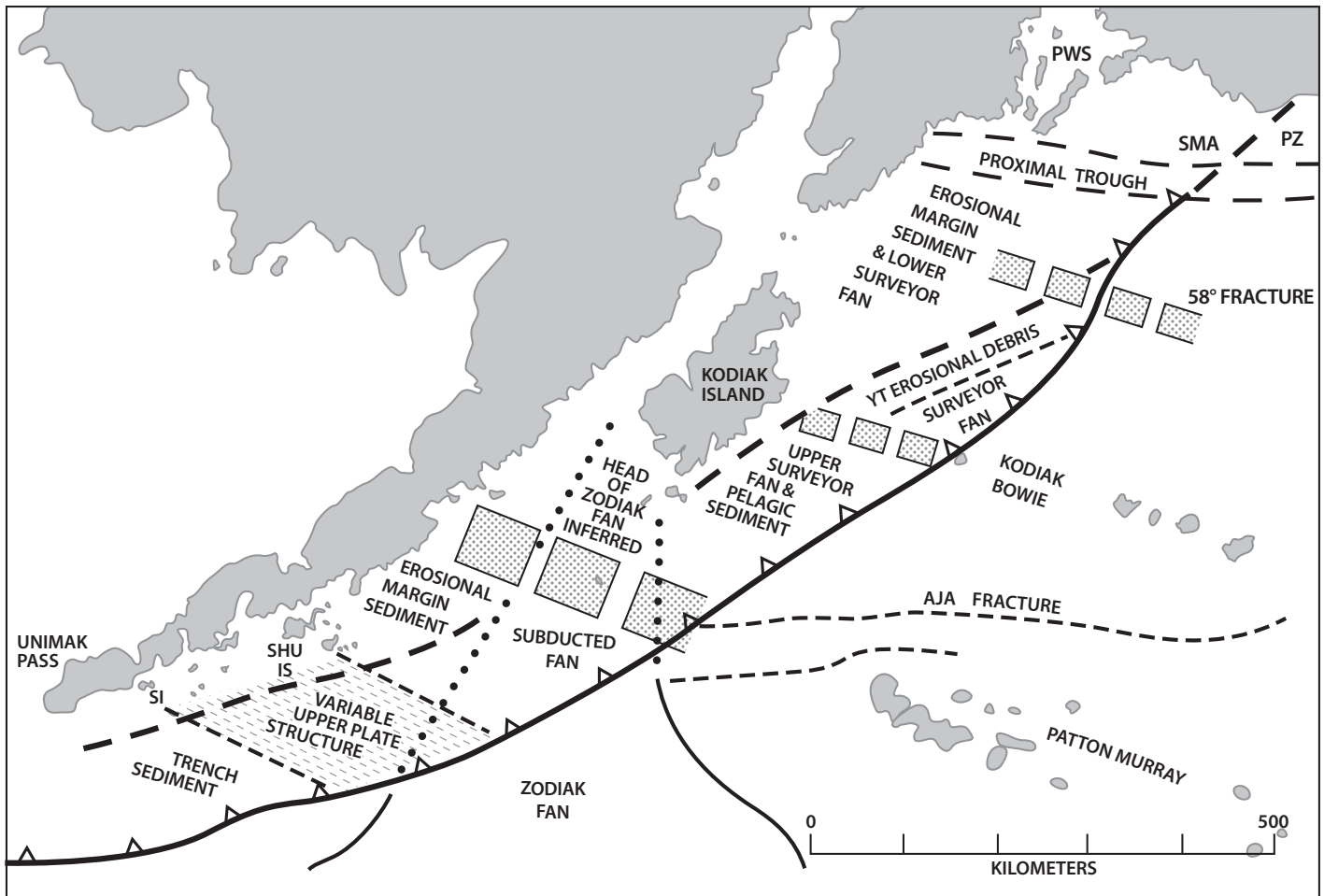


Figure 12. Material and relief in the subduction zone inferred from this study. Open squares represent inferred subducted lower plate features with 2–3 km relief. Large squares representing the subducted Patton–Murray ridge and Aja Fracture Zone indicate an uncertain width. Dashed lines in the Sanak Island (SI) and Shumagin Islands (SHU IS) areas locate the transition from the Alaska Trench to Aleutian Trench landward slopes, an area of diagonally trending deep basins. The heavy dashed line paralleling the trench represents the transition from dominantly erosional debris to dominantly subducted trench sediment. This transition occurred when glacial debris flooded the trench axis and convergent margin tectonics changed from erosional to accretionary. The uncertain age of accreted trench sediment constrains the subducted transition between 80 km and 180 km down the subduction zone. SMA—slope magnetic anomaly; PWS—Prince William Sound; PZ—Pamplona zone; YT—Yakutat terrane.

probably not significant until after 3 Ma. This constrains the extent of trench sediment on the plate interface (Fig. 12).

Reconstructing variations in the character of subduction channel sediment in other segments is estimated from indications of sediment supply. Accreted trench sediment represents the excess that is not accommodated by the subduction channel (i.e., >1 km). During accretion, the underlying subduction channel receives mostly trench sediment. If the frontal prism is composed dominantly of slope debris, it is likely that the subduction channel is receiving erosional debris. A volume balance of well-imaged Alaska Trench frontal prisms indicates that most of them can accrete in 1.25 m.y. or

less (von Huene et al., 1998; Fruehn et al., 1999; Gutscher, et al., 1998). However, distal locations on the seafloor (i.e., Site 887) received increased sediment ca. 3.5 Ma (Rea and Snoeckx, 1995). These two time estimates bracket the period of sufficient sediment for accretion of the current frontal prism. At the rate of plate convergence, the first 75–180 km of the subduction zone landward of the trench axis probably contains Surveyor fan sediment.

In the Unimak segment, the 1946 aftershocks relocated by Lopez and Okal (2006) are concentrated in a relatively small area (Fig. 9). No obvious features on the exposed seafloor of the subducting ocean plate correspond with the aftershock area. The trench axis contains

1.5-km-thick turbidite opposite Unimak Pass and 1.0 km thick opposite Sanak Basin. In both seismic images the entire section appears to subduct and the subduction channel has ample sediment. However, features of the upper plate are collocated with the aftershock area (Fig. 9). Sanak Basin limits the aftershocks on the northeast. Unimak ridge spans the aftershock area in the middle slope. The ridge is a structure unique to this segment of the convergent margin. Benthic foraminifera document subsidence of this igneous ridge and the midslope terrace consistent with the seaward tilted forearc basic strata (Fig. 10) (Bruns et al., 1987). We suggest that these observations indicate a dominant organization of seismicity by upper plate structure.

CONCLUSIONS

Along the Alaska convergent margin, subducting ocean basin seafloor relief and sediment, as well as upper plate structure, correspond with aftershock distribution of great earthquakes. The 1964 Prince William aftershocks are separated from the Kodiak aftershocks by the subducted trailing flank of the YT. Aftershocks along the Kodiak Island margin extend to its southwest end, where the Patton-Murray ridge and Aja Fracture Zone subduct. On the other side, this boundary limits the 1938 Semidi Islands aftershock area. At the end of the Alaska Peninsula, the 1946 Unimak aftershocks occurred between the diagonal Sanak Basin and Unimak Basin, both of which extend from the shelf edge down the upper slope. These basins and the unique Unimak mid-slope ridge of arc volcanic rock are features in the transition from the Alaska continental convergent margin to the Aleutian island arc. Subducted relief and upper plate structure are collocated with barriers to rupture, as well as earthquake asperities.

An asperity during the 1964 earthquake occurred where the Kodiak-Bowie ridge and its seamounts subduct. The height of Kodiak Seamount in the Alaska Trench axis is >3 km, which is a size similar to asperities and barriers associated with earthquakes elsewhere. Another asperity beneath the Kodiak shelf is collocated on the buried 58° fracture zone and its associated seamounts. Currently, areas with subducted relief are more strongly coupled than the plate interface areas between them (Zweck et al., 2002; Freymueller et al., 2008).

The 1938 Semidi Islands rupture occurred where the Kodiak fan subducts. Physical properties of the fan's Eocene deep-sea sediment differ from those of the adjacent subducted Quaternary trench sediment. The collocation of the 1938 rupture and a plate interface composed of Kodiak fan sediment indicates a possible influence of contacts of unlike material with segmentation of Alaskan earthquake rupture.

The Unimak margin displays a typical Aleutian island arc morphology. The transition area from an Alaskan to Aleutian structure contains ridges and deep basins that are most likely structure inherited from a pre-Aleutian arc period when the Alaskan and Beringian margins were continuous. This inherited structure cutting deep into the upper plate is a likely barrier to great earthquake rupture runout.

Samples from Unimak ridge indicate that the mid-slope terrace has subsided 3 km since Eocene time; this is consistent with shelf sediment strata tilted toward the trench along this entire segment. The increased steepness of the upper slope makes it prone to gravity failure

and mass wasting. The many morphological slope failure features here are consistent with a source that resulted in the 42-m-high 1946 local tsunami.

The Alaska seismogenic plate interface has both an accretionary and an erosional character. Plate interfaces of accreting margins presumably extend through trench sediment of relatively uniform materials, whereas those of eroding margins contain heterogeneous components that result in diverse types of slip (Fagereng and Sibson, 2010). Erosion along the Alaska margin is shown by Cenozoic shelf sediment sections that extend down the slope and are located close to the frontal prism. These sections are underlain by Mesozoic or early Tertiary basement that is a much older rock than the frontal prism. Trench sediment in the frontal prism could have accreted from 3 to 1.25 Ma. At the plate convergent rate, the subduction channel that formed during accretion now extends between 75 and 160 km from the trench axis, and the subduction channel from the previous erosional period is located deeper. This may explain why Bilek (2010) found the Alaska margin earthquake signature to be anomalous for accreting margins.

The geologic characteristics of the Alaska plate interface that correspond with individual rupture segments of great earthquakes help identify potential earthquake rupture segments and tsunami sources, and indicate where geodetic monitoring and geophysical surveys are most crucial.

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