Influence of the Amlia fracture zone on the evolution of the Aleutian Terrace forearc basin, central Aleutian subduction zone

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ABSTRACT

During Pliocene to Quaternary time, the central Aleutian forearc basin evolved in response to a combination of tectonic and climatic factors. Initially, along-trench transport of sediment and accretion of a frontal prism created the accommodation space to allow forearc basin deposition. Transport of sufficient sediment to overtop the bathymetrically high Amlia fracture zone and reach the central Aleutian arc began with glacialiation of continental Alaska in the Pliocene. As the obliquely subducting Amlia fracture zone swept along the central Aleutian arc, it further affected the structural evolution of the forearc basins. The subduction of the Amlia fracture zone resulted in basin inversion and loss of accommodation space east of the migrating fracture zone. Conversely, west of Amlia fracture zone, accommodation space increased arcward of a large outer-arc high that formed, in part, by a thickening of arc basement. This difference in deformation is interpreted to be the result of a variation in interplate coupling across the Amlia fracture zone that was facilitated by increasing subduction obliquity, a change in orientation of the subducting Amlia fracture zone, and late Quaternary intensification of glacialation. The change in coupling is manifested by a possible tear in the subducting Amlia fracture zone. Differences in coupling across the Amlia fracture zone have important implications for the location of maximum slip during future great earthquakes. In addition, shaking during a great earthquake could trigger large mass failures of the summit platform, as evidenced by the presence of thick mass transport deposits of primarily Quaternary age that are found in the forearc basin west of the Amlia fracture zone.

INTRODUCTION

Sedimentary basins around island arcs provide some of the most complete records of active-margin tectonic evolution. Forearc basins, in particular, form structurally and fill with sediment in response to a complex interplay between tectonic controls and sediment sources (e.g., Dickinson, 1974, 1995; Marsaglia and Ingersoll, 1992; Underwood et al., 1995). In addition to providing a record of the tectonic history of a convergent margin, the location of forearc basin depocenters may record the locations of areas of large slip along the megathrust during great subduction zone earthquakes (e.g., Wells et al., 2003; Song and Simons, 2003; Fuller et al., 2006; Llenos and McGuire, 2007; Rosenau and Oncken, 2009). Since forearc basins are long-lived features, they serve as a record of subsidence above the plate interface over time scales on the order of a million years. We investigated what forearc basin evolution can tell us about the relative importance of various subduction-zone characteristics in causing great earthquakes, which remains challenging to assess, given the relative rarity of such events. Here, we analyzed the Pliocene and Quaternary evolution of forearc basin depocenters along the central Aleutian convergent margin. The Alaska-Aleutian subduction zone is one of the longest in the world and is capable of producing great earthquakes that generate transoceanic tsunamis. This section of the Alaska-Aleutian subduction zone has produced great, tsunamiogenic earthquakes in the recent past, including the Mw 8.6 event in 1957, which caused significant damage to structures in Hawaii from tsunami waves as high as 16 m (Lander and Lockridge, 1989).

The central Aleutian subduction zone is an obliquely subducting margin where large structures on the downgoing plate propagate along the arc, affecting the forearc in a time-transgressive manner. The main structure we focus on is the impact of the westward-propagating Amlia fracture zone on the evolution of the central Aleutian forearc basin and the associated amount of coupling along the plate interface. The forearc basin response to fracture zone propagation is documented in differences in style of deformation and the location and migration of basin depocenters. This study examines the sedimentary architecture in detail over a broad area of the central Aleutian forearc basin, incorporating age control based on Deep Sea Drilling Project (DSDP) cores recovered at sites 186 and 187. We link forearc stratigraphy to (1) the westward propagation of the Amlia fracture zone through time, (2) the importance of strike-slip faulting in the forearc as subduction becomes more oblique, (3) the relatively rapid evolution of forearc structures during the last 1 m.y., including the influence of climate on trench sedimentation and plate coupling. Finally, by comparing evidence for processes that affect the along- and across-strike structural and stratigraphic character of the forearc, we evaluate the potential for the central Aleutian forearc region to produce tsunamis triggered by great earthquakes.
GEOLOGIC AND TECTONIC SETTING

The present configuration of the central Aleutian forearc is the result of tectonic evolution dating at least to early Eocene time. The Aleutian Ridge is subdivided generally into three chronostratigraphic units known as the lower, middle, and upper series (Scholl et al., 1983, 1987), which reflect three major phases of tectonic evolution of the arc since the Eocene, ca. 50 Ma. The lower series formed during an initial, constructive phase of voluminous arc magmatism that accompanied subduction of the Kula plate (Scholl et al., 1983, 1987). Formation of the Oligocene to late Miocene middle series is thought to have accompanied a phase of substantially reduced magmatism, and erosion and subsidence of the arc platform (Scholl et al., 1983, 1987). The middle and lower series underlie the modern forearc basin and do not exhibit basin-filling sedimentation, which indicates that the Aleutian arc in this region did not include a true forearc basin depression until after late Miocene time (Scholl et al., 1983, 1987; Harbert et al., 1986). At ca. 5–6 Ma, an accretionary frontal prism formed as the result of significant sediment underthrusting, likely triggered by an increase in sediment supply to the trench following enhanced glacial erosion in southeastern Alaska after the Yakutat–North America collision began (Scholl et al., 1987; Gulick et al., 2007). An outer-arc high formed as the result of accretion and underplating of sediment beneath the arc massif along a primary splay fault. This created the accommodation space for the deposition of sediment in the forearc basin. Upper-series deposits fill the forearc basin depocenters, resting unconformably on or faulted against middle- and lower-series rocks; thus, the forearc basin is underlain entirely by arc massif. Forearc basin deposits are composed of volcaniclastic and pelagic sediment (e.g., Scholl et al., 1987).

Figure 1. Location map showing study area in the Andreanof Islands, which stretch from Tanaga to Amukta Islands. The entire Aleutian arc is shown in the inset, including marine magnetic anomalies from Atwater (1989). Topography and bathymetry for both maps are from Lim et al. (2009). The outlines of Atka Basin (AB) and Hawley Ridge (HR) are dashed in white. Multichannel seismic-reflection (MCS) track lines are shown by yellow lines; those displayed as figures are labeled. Locations of heat-flow sites are shown by stars (GeoPRISMS Data Portal, 2011). White dots on Aleutian Ridge delineate the subsided southern edge of the summit platform. Hawley Ridge shear zone (HRSZ) is shown by red line. The Andreanof block (modified from Geist et al., 1988) is shown by thin white line and stippled pattern. AFZ—Amlia fracture zone; DSDP—Deep Sea Drilling Project.
Outer forearc basin sediment was sampled at DSDP site 186 and consisted predominately of diatomaceous silty clay and ooze with interbedded volcanic ash and pumice, as well as laminated, volcaniclastic sand-and-silt turbidites as thick as >4 m (Scholl and Creager, 1973; Stewart, 1978). The volcaniclastic deposits evidently were derived largely from the Aleutian arc, to the north, delivered from the arc front via submarine canyons that debouch into the forearc basin (Underwood, 1986).

In the region of the Andreanof Islands, the oceanic crust of the Pacific plate obliquely underthrusts (30° to normal) the Aleutian island arc (DeMets et al., 2010). In order to accommodate shear stress along the subduction zone caused by oblique convergence, the Aleutian Ridge has separated into blocks that rotate clockwise and translate to the west (Spence, 1977; Geist et al., 1988). The Andreanof block is defined geomorphically, seismically, and paleomagnetically as extending from Adak Canyon to east of Seguam Island (Fig. 1; LaForge and Engdahl, 1979; Geist et al., 1988). Geist et al. (1988) used geomorphic and structural elements of the arc massif imaged on seismic-reflection profiles, supported by paleomagnetic data from Amlia Island (Hartbert, 1987), to show that the eastern sector of the Andreanof block has rotated 15°–25° clockwise about a vertical axis, with associated strike-slip offset in the forearc and formation of pull-apart basins along the arc summit. Seafloor imagery and seismic-reflection profiles indicate that oblique convergence also causes right-lateral strike-slip offset along the Hawley Ridge shear zone, which forms the southern margin of the Andreanof block (Ryan and Scholl, 1989). Along the northern edge of the Andreanof block, a complex shear zone accommodates slip partitioning within the volcanic arc (Ekstrom and Engdahl, 1989; Lallemant and Oldow, 2000). The shallow upper plate at the eastern end of the Andreanof block is deformed by transverse left-lateral strike-slip and normal faulting (Ruppert et al., 2012).

A major structure on the Pacific plate underthrusting the central Aleutian Ridge is the Amlia fracture zone. The Amlia fracture zone is an ~1-km-high, 20- to 40-km-wide bathymetric feature now situated near longitude 173°W (Fig. 1). Owing to oblique subduction, the Amlia fracture zone is currently migrating westward along the margin at a rate of over 2 cm/yr (DeMets, et al., 2010). It juxtaposes 57 m.y. oceanic crust on its west side against 65 m.y. crust to the east; magnetic lineations are offset 220 km in a left-lateral sense across the fracture zone. The older seafloor on the Pacific plate east of the fracture zone is several hundred meters deeper than that to the west. In addition, the younger seafloor west of the Amlia fracture zone exhibits a more complex bathymetry, with the presence of more small seamounts on the subducting plate (Fig. 2; Lonsdale, 1988). The Amlia fracture zone forms a barrier that effectively reduces the volume of westward sediment transport by turbidity currents along the trench, leading to greater thickness of trench.

Figure 2. GLORIA (Geological LOng-Range Inclined Asdic) sidescan sonar imagery (Paskevich et al., 2010) showing high backscatter reflecting relief on the Pacific plate. West of Amlia fracture zone (AFZ), the subduction plate has more relief than to the east. The white line shows location of arcward edge of the trench.
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sediment, and corresponding greater flux of sediment-derived melt in arc magmatism, east of the fracture zone compared to west of it (Scholl et al., 1982; Kelemen et al., 2003).

The subduction of the Amlia fracture zone has influenced the local seismicity. Most notably, since the 1960s, there have been fewer M >5 thrust earthquakes on the plate boundary east of the Amlia fracture zone, from 173°W to ~171°W, than have occurred on adjacent segments of the arc (Fig. 3; Ekstrom and Engdahl, 1989). Both the axis of volcanism and the Wadati-Benioff zone are offset across the Amlia fracture zone (House and Jacob, 1983). Based on stress inversions of focal mechanisms, Lu and Wyss (1996) indicated that there are major changes in stress directions across the fracture zone. Although it is apparent that the subduction of the Amlia fracture zone affects seismicity, it apparently did not form a barrier to rupture during the 9 March 1957, Mw 8.6 Andreanof earthquake, the fourth largest earthquake to occur within the United States during historic times (Johnson et al., 1994). Unfortunately, the source parameters of the 1957 event are not well constrained because the earthquake occurred prior to the deployment of digital broadband seismometers. Johnson and Satake (1993) inverted tsunami waveforms to determine that the largest slip patches occurred west of the Amlia fracture zone. Few aftershocks occurred and little moment was released east of Amlia fracture zone, and thus rupture propagated across the Amlia fracture zone with reduced moment release. More recently, the Mw 8.0 in 1986 (Hwang and Kanamori, 1986; Engdahl et al., 1989) and Mw 7.9 in 1996 (Kisslinger and Kikuchi, 1997) megathrust earthquakes occurred beneath the Andreanof Islands, with all the moment released west of the Amlia fracture zone during these events.

In geodetic studies of the Aleutian Islands, Cross and Freymueller (2007) and Freymueller et al. (2008) used global positioning system (GPS) measurements to show that there is strong coupling between the upper and lower plates in the western part of the Andreanof block and little to no coupling in the eastern part of the Andreanof block. The boundary between the strongly coupled and weakly coupled regions coincides approximately with the Amlia fracture zone. GPS strain measurements show that, for example, sites on Atka Island move ~5 mm/yr toward the southwest, whereas sites on Adak Island move 10–15 mm/yr toward the northwest (Freymueller et al., 2008). The area of the megathrust that ruptured in the 1986 Andreanof earthquake and the area of highest moment release during the 1957 Andreanof earthquake both occurred offshore of Adak Island, which is now nearly 100% locked (Cross and Freymueller, 2007).

DATA

In this study, we reinterpreted multichannel seismic-reflection (MCS) data collected in 1980

Figure 3. Earthquakes are for Global Centroid Moment Tensor (CMT) thrust solutions of M 5–6 (yellow), M 6–7 (orange), M 7–8 (green), and M >8 (red) dating from 1976 to 2010 (http://www.globalcmt.org/). The locations of significant earthquake epicenters (1957, 1986, and 1996) are labeled. The depth to the top of the subducting Pacific plate (in km) is shown by red lines (Hayes et al., 2012). Note the shallow depth of the plate beneath Adak Island.
and 1981 by the U.S. Geological Survey offshore of the Andreanof Islands (Fig. 1). These profiles were collected using a five air-gun, 2000 psi tuned source array with a total volume of 1315 in^3 (0.0215 m^3) producing shots with 50 m spacing. Data were recorded using a 2.4-km-long, 24 channel hydrophone streamer and a GUS 4200 digital recorder. We also utilized a seismic-reflection profile collected by a joint effort of the Woods Hole Oceanographic Institution, U.S. Geological Survey, and Lamont-Doherty Earth Observatory on the R/V Maurice Ewing in 1994 (1232E994 on Fig. 1). This profile was collected in 1994 using an 8400 in^3 (0.138 m^3) air-gun array source and a 160 channel, 4-km-long multichannel hydrophone streamer. All MCS data were migrated using a poststack finite-element migration algorithm with the migration velocities chosen from constant-velocity migration panels. A band-pass filter (5–40 Hz) and automatic gain control were applied to the data.

Age control for reflectors within the forearc basin was determined by a direct tie of reflectors on profiles 7L981 and 10L981 to DSDP site 186, drilled into a condensed section of the outer forearc basin on the antiformal outer arc (Fig. 1; Scholl and Creager, 1973; Scholl et al., 1987). DSDP site 186 penetrated to a depth below seafloor of 926 m, with 143 m of core recovery. The core at site 186 had a basal age of late Miocene to early Pliocene; displaced blocks of middle Miocene sediment occurred within the Upper Pliocene section (Scholl and Creager, 1973). The depths to several key stratigraphic horizons, including the base of the Lower Pliocene (5.3 Ma), top of the Lower Pliocene (3.6 Ma), top of the Upper Pliocene (2.6 Ma), and top of the Upper Pleistocene (800 ka), were determined by diagnostic fossil assemblages including diatoms, radiolarian, and foraminifera analyzed by the DSDP shipboard party (Scholl and Creager, 1973). Depths to these horizons were converted to two-way traveltime using P-wave velocities measured on the core (1.65–2.0 km/s; Creager and Scholl, 1973). We used stratigraphic horizons extrapolated from DSDP site 186 to generate isopach maps defining sediment thickness in the forearc basin for each time interval. Sediment thicknesses were converted from two-way traveltime to depth using a velocity of 2 km/s, consistent with refraction velocities measured over the forearc basin and interval velocities calculated from MCS stacking velocities; the velocity data available did not justify a more detailed velocity model. The isopach data were gridded using a radial basis function over a 20 km by 50 km window oriented along the axis of the forearc basin.

**INTERPRETATIONS**

The focus of this paper is on the most recent phase of tectonics as expressed in the Pliocene and Quaternary deposits of the forearc basin. An outer-arc high formed as the result of accretion of sediment beneath the arc massif along a primary splay fault, which created accommodation space for the deposition of forearc basin sediment (Harbert et al., 1986). Additional accommodation space was created by the progressive uplift of the outer-arc high in response to movement on the splay fault. Although the forearc basin initially formed in response to accretion of sediment at the trench and formation of an outer-arc high, it is evident that the present structure and sedimentary architecture of the forearc basin vary substantially along strike. In particular, the basin shape, depositional style, and syn- and postdepositional deformation are notably different on either side of 173°W, where the Amlia fracture zone is subducting. Stratigraphic horizons that are correlated across the forearc basin and tied to DSDP site 186 for age control are used to describe how the forearc basin has evolved through space and time on either side of the fracture zone.

Forearc basin depocenters lie beneath the Aleutian Terrace, a prominent geomorphic feature that lies between the summit platform and trench at water depths of 3–4 km (Fig. 1). Although the terrace is a relatively flat feature, it is punctuated by bathymetric highs and lows, including Atka Basin and Hawley Ridge (Fig. 1). Atka Basin lies immediately west of the northward projection of the Amlia fracture zone and is the largest subbasin (80 km by ~35 km) within this part of the Aleutian Terrace forearc basin (Fig. 1). West of Atka Basin, the Aleutian Terrace is bordered at its southern end by Hawley Ridge, a prominent outer-arc high over 200 km long that extends from western Atka Island to west of Adak Island (Fig. 1). Hawley Ridge stands ~1000 m above the Aleutian Terrace, with the maximum height of the ridge off Adak Island; there is no prominent outer-arc high along the seaward edge of the terrace south and east of Atka Basin. North of Hawley Ridge, the seaward edge of the summit platform has been steepened from near horizontal to dipping south as much as 6°. This deformation of the arc platform is most evident off Adak Island, where the outer edge of the arc platform is now located at a depth of 1300 m. East of the location where the Amlia fracture zone is now subducting (south of Seguam and eastern Amlia Islands), the Aleutian Terrace shallows in elevation to a few hundred meters higher than the terrace elevation west of the Amlia fracture zone (Fig. 1), and the arc massif has rotated into the forearc, as evident in bathymetry off of Seguam Island (Fig. 1; Geist et al., 1988).

Between Adak and Atka Islands, the Aleutian Terrace forearc basin shows a typical forearc basin configuration with evidence for progressive uplift of an outer arc forming the seaward side of the forearc basin (Figs. 4–6). North of Hawley Ridge, the geometry of the Pliocene–Quaternary horizons indicates that the outer-arc high has been uplifting actively throughout this time period; in particular, recent uplift is evident just north (arcward) of DSDP site 186 (Fig. 4). The arcward edge of the forearc basin generally shows onlap of basin sediment onto the older middle Miocene and arc framework rock, with little deformation. However, the western lines shows that strata along the northern edge of the forearc basin dip toward the trench, which, combined with the arcward dip of outer forearc basin strata, show evidence of additional shortening across the margin (Figs. 5 and 6). The westernmost profile shows a relatively narrow basin geometry with ample remaining accommodation space, and arcward migration of the depocenter with time (Fig. 6).

Near the intersection of the Amlia fracture zone with the Aleutian Terrace, there is a transition between the style of forearc basin deformation observed east and west of the fracture zone (Fig. 7). Here, the seaward edge of the basin has been truncated by extensional and/or strike-slip deformation along the Hawley Ridge shear zone. As a result, the forearc basin is perched with little accommodation space, but with substantially less relief at the seaward side of the basin than is evident in profiles to the east. East of the Amlia fracture zone, normal offset of Pliocene through Holocene reflectors at the seaward slope has resulted in the collapse of the seaward side of the forearc basin (Figs. 8 and 9). This extensional collapse of the forearc with as much as 1800 m of relief has effectively transformed the forearc basin into a perched basin with little to no remaining accommodation space. In the area where the Aleutian Terrace shallows south of Seguam Island, horst and graben structures deform uplifted basin sediment (Fig. 9). A subordinate (trench-slope) basin occurs at the seaward side of the collapsing forearc that is narrower than the main forearc basin (5–10 km compared to 40–50 km) and contains much thinner sedimentary fill (<1 km compared to 2–4 km). The location of the normal-fault–bounded trench-slope basin approximately coincides with the location where the Hawley Ridge shear zone intersects the eastern part of the study area (Ryan and Scholl, 1989).

Although forearc basin deformation is dominated by normal faulting east of the Amlia fracture zone, lower Pliocene reflectors show
Figure 4. (A) Profile 10L981 crosses forearc at Deep Sea Drilling Project (DSDP) site 186. HRSZ—Hawley Ridge shear zone. (B) Close-up of area shown in box in A. Note progressive dip of outer forearc basin reflectors as the result of uplift of the outer-arc high. Transparent yellow unit denotes unusually thick mass transport deposits; the yellow arrow points to the seaward extent of more recent mass transport deposits. Dark blue—base of upper-series forearc basin; red-brown—top of Lower Pliocene; light blue—top of Upper Pliocene; green—top of Lower Pleistocene; and orange—reflector within Upper Pleistocene (too shallow to be tied directly to DSDP site). Location of profile is shown in Figure 1. TWTT—two-way traveltime; V.E.—vertical exaggeration.
Figure 5. (A) Profile 6L981 crosses Hawley Ridge in the western sector of the Andreanof block. HRSZ—Hawley Ridge shear zone. (B) Close-up of area shown in box in A. Note back thrust deforming the entire forearc basin section at the arcward edge of Hawley Ridge. Transparent yellow unit denotes unusually thick mass transport deposits. Dark blue—base of upper-series forearc basin; red-brown—top of Lower Pliocene; light blue—top of Upper Pliocene; green—top of Lower Pleistocene; and orange—reflector within Upper Pleistocene (too shallow to be tied directly to Deep Sea Drilling Project site). Location of profile is shown in Figure 1. TWTT—two-way traveltime; V.E.—vertical exaggeration.
Figure 6. (A) Profile 5L981 crosses Hawley Ridge offshore of Adak Island. The summit platform is tilted down toward the trench (see also Fig. 1). HRSZ—Hawley Ridge shear zone. (B) Close-up of area shown in box in A. Note seaward tilt of forearc basin sediment at the arcward end of the forearc basin. No mass transport deposits are imaged within the forearc basin. Dark blue—base of upper-series forearc basin; red-brown—top of Lower Pliocene; light blue—top of Upper Pliocene; green—top of Lower Pleistocene; and orange—reflector within Upper Pleistocene (too shallow to be tied directly to Deep Sea Drilling Project site). Location of profile is shown in Figure 1. TWTT—two-way traveltime; V.E.—vertical exaggeration.
Figure 7. (A) Profile 12L981 crosses the forearc just west of its intersection with Amlia fracture zone. HRSZ—Hawley Ridge shear zone. (B) Close-up of area shown in box in A. Note truncation and removal of outer forearc basin strata. Transparent yellow units denote unusually thick mass transport deposits. Dark blue—base of upper-series forearc basin; red-brown—top of Lower Pliocene; light blue—top of Upper Pliocene; green—top of Lower Pleistocene; and orange—reflector within Upper Pleistocene (too shallow to be tied directly to Deep Sea Drilling Project site). Location of profile is shown in Figure 1. TWTT—two-way traveltime; V.E.—vertical exaggeration.
Figure 8. (A) Profile 13L580 crosses the forearc east of Amlia fracture zone. HRSZ—Hawley Ridge shear zone. (B) Close-up of area shown in box in A. Note trenchward tilt of the forearc basin and lack of accommodation space. Normal offset faults suggest extensional collapse of outer forearc basin. No thick mass transport deposits are imaged within the forearc basin. Dark blue—base of upper-series forearc basin; red-brown—top of Lower Pliocene; light blue—top of Upper Pliocene; and orange—reflector within Upper Pleistocene (too shallow to be tied directly to Deep Sea Drilling Project site). Location of profile is shown in Figure 1. Figure 11 shows area of B flattened to the orange horizon.

TWTT—two-way traveltime; V.E.—vertical exaggeration.
Figure 9. (A) Profile 1232E994 crosses the forearc offshore of Seguam Island. HRSZ—Hawley Ridge shear zone. (B) Close-up of area shown in box in A. Normal offset faults deform elevated area of Aleutian Terrace. No mass transport deposits are imaged within the forearc basin. Dark blue—base of upper-series forearc basin; red-brown—top of Lower Pliocene; light blue—top of Upper Pliocene; green—top of Lower Pleistocene; and orange—reflector within Upper Pleistocene (too shallow to be tied directly to Deep Sea Drilling Project site). Location of profile is shown in Figure 1. TWTT—two-way traveltime; V.E.—vertical exaggeration.
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Evidence for an earlier phase of compressional deformation. Basin sediments deposited during the Pliocene show syndepositional uplift of the seaward side of the basin with onlap at the north end of the basin. In addition, Lower Pliocene strata are higher than coeval strata beneath the center of the forearc basin, even though this pattern was subsequently inverted, with middle Pleistocene reflectors now at a lower elevation beneath the outer forearc than beneath the center of the forearc basin (Figs. 8 and 9). We flattened the reflection profile 13L580 on a reflector that has a post–early Pleistocene age (<800 ka; Fig. 10). Prior to this time, the forearc basin strata were gently dipping (had not yet been tilted significantly seaward), and the reflectors show the development of an outer-arc high with arcward-dipping reflectors to the south, and onlap onto the north. Thus, relatively recently, the basin was configured similar to the forearc basin west of the Amlia fracture zone (e.g., compare to Fig. 5).

Beneath the Aleutian Terrace, multiple depocenters are evident from isopach maps (Fig. 11). Depocenters that contain more than 2.4 km of sediment occur beneath Atka Basin and behind (north of) Hawley Ridge (80 km to the northwest of Atka Basin). In general, forearc basin depocenters migrate north and west with time; forearc basin strata east of the Amlia fracture zone are generally deposited farther seaward and are older than the deposits further west (Fig. 11). During the early Pliocene, depocenters were generally smaller and more discontinuous, with little accumulation of sediment in a forearc basin north of Hawley Ridge. Sedimentation was concentrated beneath the modern Atka Basin during late Pliocene time, with the depocenter having clearly moved toward the arc. During the early Pleistocene (post-Pliocene and pre–ca. 800 ka), overall sediment accumulation was much lower, with little accumulation in localized depocenters such as Atka Basin. The depocenter north of Hawley Ridge initially formed during the early Pleistocene, but only ~400 m of sediment accumulated. A major episode of basin deposition began during the late Pleistocene. At this time, Hawley Ridge was uplifted, as shown by the elevation of the top of the Lower Pleistocene reflector (Fig. 5). A thickness of more than 1200 m of sediment was deposited in the depocenter north of the ridge, with an additional 500 m deposited beneath Atka Basin. Migration of the depocenter northward toward the arc, especially in the western part of the study area, is consistent with the active uplift of Hawley Ridge. Thus, the major uplift of the 1-km-high Hawley Ridge combined with the deposition of the thickest forearc basin sediment all occurred relatively recently within the last 800 k.y. By middle Pleistocene time, the forearc basin east of the Amlia fracture zone had been inverted and had little remaining accommodation space, and it has accumulated little sediment since that time.

Figure 10. Profile 13L580 flattened on reflector within the Upper Pleistocene (orange horizon in Fig. 8). Once flattened, the reflectors at the arcward end of the basin onlap onto older strata, and reflectors at seaward end are tilted arcward above an outer-arc antiform. TWTT—two-way traveltime.

In addition to temporal and spatial changes in the loci of sediment deposition, there are also changes in depositional processes as indicated by the character of forearc basin reflectivity. Forearc basin deposits are generally composed of regular, well-defined parallel layering that suggests that turbidites constitute most of the basin fill; turbidites were sampled within the outer forearc basin at DSDP site 186 (Scholl and Creager, 1973). However, intercalated between the layered reflectors, there are acoustically chaotic to transparent units that often erode or truncate units below (e.g., Fig. 4). We interpret these units to be mass transport deposits that interfinger with and disrupt turbidite deposition within the basin. The distribution of mass transport deposits beneath the Aleutian Terrace varies both spatially and temporally along strike. East of Amlia fracture zone, mass transport deposits are notably absent from the easternmost profile south of Seguam Island (Fig. 9) and, when present, are thin, areally restricted, and are confined to the Pliocene section (Fig. 8). Mass transport deposits are much more common west of Amlia fracture zone and are observed on every along- and across-strike seismic profile west of 173°W, with the exception of the westernmost line (Fig. 6). Commonly, one-third to one-half of the basin-fill thickness has stratification disrupted by mass transport deposits, which in places are thicker at the arcward (north) side of the basin than at the seaward side (e.g., Figs. 5 and 7). Three of the profiles that cross the entire...
Figure 11. Isopach maps of forearc basin strata for the Lower Pliocene (5.3–3.6 Ma), Upper Pliocene (3.6–2.6 Ma), Lower Pleistocene (2.6–0.8 Ma), and Upper Pleistocene–Holocene (post–0.8 Ma). Thickness is in meters assuming a sediment velocity of 2000 m/s. Interpretations are based on tying stratigraphic calls from Deep Sea Drilling Project site 186 to multichannel and single-channel seismic-reflection profiles available at http://walrus.wr.usgs.gov/NAMSS. The dashed white line shows the location of the present-day Atka Basin. HRSZ—Hawley Ridge shear zone; AT—Aleutian Trench.
width of the forearc show mass transport deposits composed of 400–450-m-thick packages of acoustically chaotic reflectors (Figs. 4, 5, and 7). Although these deposits may represent amalgamated events and thus may not have formed at one specific time, the deposits appear to be confined to specific time intervals. Line L91281 (Fig. 7) is the only profile to show a relatively thick mass transport deposit (~420 m) of Pliocene age, with the majority of other thick mass transport deposits deposited during the Quaternary. The thickest mass transport deposits off Amlia Island (Figs. 4 and 7) were deposited prior to the horizon we correlated within the late Pleistocene; on the westernmost profile where we imaged mass transport deposits (Fig. 5), the thickest deposit is younger than that horizon. Based on available data, the distribution of the thickest mass transport deposits appears to have migrated to the west with time, but not as far west as Adak Island.

INFLUENCE OF AMLIA FRACTURE ZONE ON FOREARC BASIN EVOLUTION

We used the patterns of forearc sediment deposition and deformation to interpret central Aleutian tectonic history in detail. A major influence in the evolution of the forearc basin is the interaction of the Amlia fracture zone with the margin. The Pacific–Kula–North American plate reconstructions of Lonsdale (1988) were used to determine the location of the Amlia fracture zone with respect to the margin. The Pacific–Kula–North America relative plate motion has been constant since 11 Ma (Atwater and Stock, 1998), we used the current relative plate motion near the Amlia fracture zone (51°N, 173°W) of 72 mm/yr (DeMets et al., 2010) in our reconstructions. At ca. 56–55 Ma, the orientation of Pacific spreading fabric, including associated fracture zones, changed abruptly, as indicated by a remnant of the dead Kula-Pacific spreading center captured south of the Aleutian Trench (Lonsdale, 1988). Between magnetic anomalies 24 and 24.2, the orientation of the Amlia fracture zone changed from approximately N42°W (current Pacific–North America relative plate motion) to approximately N-S (current orientation of the Amlia fracture zone south of Aleutian Trench) (Fig. 12). It is not known how this rotation occurred, but it is likely that the Kula-Pacific spreading center was segmented into shorter axes, as evidenced by irregular, oblique fracture zones west of the Amlia fracture zone (Lonsdale, 1988). In Lonsdale’s preferred reconstruction, the Amlia fracture zone is one of the few fracture zones to persist through this plate reorganization. Kula-Pacific spreading ceased at ca. 43 Ma (anomaly 18r), and the end of the Amlia fracture zone adjacent to the spreading center would have begun to subduct.

Figure 12. Lonsdale’s (1988) preferred reconstruction of the Amlia Fracture Zone (AFZ) and magnetic anomalies 18 (FSC—fossil spreading center) through 31 (see also Atwater, 1989). The locations where the Amlia fracture zone intersected the Aleutian trench back through time are shown by green dots. The change in orientation of the trench axis occurs between the dots labeled 3.6 Ma and 2.6 Ma.
at ca. 10 Ma at a location 190 km east of its present location (Figs. 12 and 13).

The rate at which the Umlia fracture zone sweeps along the Aleutian arc has increased through time, not only as a result of changes in the orientation of the fracture zone itself (as discussed already), but also owing to along-arc changes in the orientation of the trench axis that affect the obliquity of plate motion (Fig. 12). Although the Aleutian Trench is generally considered to be arcuate, along the central Aleutians, the trench is composed of sections that are quite linear. East of ~171°W, the Aleutian trench trends N69°W over a distance of 750 km to near Unimak Pass, whereas west of ~171°W, the trench is oriented at N87°W. This results in an increase of obliquity of 18° over a relatively short distance. East of the change in trench orientation, the relative plate motion resolves into 26 mm/yr along strike and 67 mm/yr perpendicular to strike. West of the change, the plate motion resolves into 48 mm/yr along strike and 53 mm/yr perpendicular to strike. The Umlia fracture zone would have arrived at this change in trench orientation at ca. 3.6 Ma (Fig. 12).

Prior to the Pliocene (5.3 Ma), the position of the Umlia fracture zone with respect to the trench would have been relatively stationary and only migrated along the trench for a distance of ~10 km, owing to the slight obliquity of the trench axis with respect to the plate vector (Fig. 12). As the trend of the subducting Umlia fracture zone changed to a more northerly orientation (Lonsdale, 1988), the rate of along-arc motion increased (Fig. 12). Although the change in orientation of the Umlia fracture zone is shown as a gentle bend in Figure 12, it is not known exactly how the change in orientation from N44°W (anomaly 23 and younger) to N2°W (anomaly 25 and older) occurred. Anomaly 24.1 along the Umlia fracture zone would have arrived at the Aleutian Trench at about the same time as, or slightly after the arrival of the Umlia fracture zone at the change in trench orientation. The intersection of the Umlia fracture zone at anomaly 25 would have arrived at the trench at 2.1 Ma near a location along the trench south of Seguam Island, 90 km east of the fracture zone’s present position (Fig. 12). It has only been in about the last 2 m.y. that the Umlia fracture zone has propagated to the west in its present configuration and rate.

While the Umlia fracture zone propagates to the west, its location with respect to the Aleutian Terrace forearc basin is also a function of whether slip partitioning between strike-slip faults within the forearc and dip-slip along the megathrust occurs in the central Aleutian subduction zone. In general, if obliquity along a subduction zone is greater than ~30°, slip is generally partitioned between slip along the megathrust and strike-slip faults in the upper plate (McCaffrey, 1992). Complete slip partitioning would result in subduction occurring perpendicular to the trench axis, with faults within the upper plate accommodating all of the along-arc motion. Ekstrom and Engdahl (1989) estimated that for the central Aleutian subduction zone, ~60% of the along-arc slip is partitioned to strike-slip faults in the upper plate based on the average discrepancy between slip vector and plate motion between 172°W and 179°W. The strike-slip faults in the upper plate would then take up the 60% of the along-arc right-lateral motion or ~27 km/m.y. In the upper plate, strike-slip faults are located both along the line of volcanism on the Aleutian Ridge and in the forearc along the Hawley Ridge shear zone (Fig. 1). How much of the 27 km/m.y. slip is partitioned to the Hawley Ridge shear zone will determine the rate at which the Umlia fracture zone propagates along the arc with respect to the forearc basin. Since we do not know how this slip is partitioned, we cannot accurately restore

Figure 13. Reconstruction of the Pacific plate back to 10 Ma when the Kula Ridge (18r [FSC—fossil spreading center]) first arrived at the Aleutian Trench based on Lonsdale (1988). It is assumed that over this time period, the plate motion has been constant (Atwater and Stock, 1998). The orientation of relative plate motion (shown by gray arrow) is close to parallel to the orientation of the Umlia fracture zone between anomalies 21 and 18r.
the location of the forearc basin depocenters back through time. However, prior to 2 Ma, when arc-parallel strike-slip motion accelerated, the locations of the depocenters would have been relatively static.

Slip partitioning within the upper plate is accommodated by both strike-slip faulting and block rotation (Fig. 1; Geist et al., 1988). The eastern edge of the rotating Andreanof block and the eastern extent of the Hawley Ridge shear zone both occur near the change in orientation of the Aleutian Trench, which consequently also coincides with the resultant increase in along-arc motion of the Amlia fracture zone–trench intersection. Although the Hawley Ridge shear zone extends along the entire southern length of the Andreanof block, only the eastern Andreanof block has rotated (compare summit platform east and west of Amlia fracture zone in Fig. 1). The difference in the amount of rotation between the eastern and western portions of the Andreanof is inferred to cause significant flexing within the block (Geist et al., 1988). The internal deformation of the Andreanof block is manifested by west-directed shortening beneath the Aleutian Terrace (Fig. 14) and perhaps also by the presence of a large tholeiitic volcano at Atka Island, possibly formed by faster magma ascent facilitated by fractured rock within the Andreanof block (Kay et al., 1982). A 40 km right-lateral offset perpendicular to the arc of the downgoing plate near 173°W (location of Amlia fracture zone) was resolved by House and Jacob (1983); they suggested that this offset may be accommodated gradually by flexure or by a single tear in the plate. The orientation of a focal mechanism resolved by Ekstrom and Engdahl (1989) is consistent with a tear in the subducting plate. As the offset of the plate along the Amlia fracture zone propagates to the west, a mass deficiency between the upper and lower surface of the arc could result in the upwelling of asthenosphere along a slab tear (House and Jacob, 1983).

We suggest that a slab tear at the Amlia fracture zone could be facilitated by variations in the along-arc component of motion across the fracture zone, which could impart additional stresses on the subducting plate resulting, in a tear along a slab weakness (the fracture zone). The plate west of the change in trench orientation would experience a larger component of along-arc stress than that to the east. Once the slab is offset along the fracture zone, the older plate to the east would be free to roll back, allowing space for the rotation of the Aleutian Ridge into the forearc. As House and Jacob (1983) suggested, the plate offset could result in upwelling of asthenospheric material beneath the forearc. This hypothesis is supported by (1) warm thermal anomalies based on two heat-flow sites that show values near 100 mW/m² (Fig. 1; GeoPRISMS Data Portal, 2011) and perhaps associated higher elevation of the Aleutian Terrace south of Seguam Island (Fig. 1), (2) a zone of low seismicity for M >5 thrust earthquakes.
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between Amila and Amukta Islands (Fig. 2), and (3) the altered chemistry of volcanics enriched in serpentinite on Seguam Island (Singer et al., 2007), and refraction data showing the mantle wedge located less than 40 km from the trench at the trenchward edge of the elevated terrace (Holbrook et al., 1999).

Conversely, the partially detached slab west of the Amlia fracture zone is younger and therefore somewhat more buoyant, resulting in a shallowing of the subducting slab (Hayes et al., 2012), indicating the slab is as shallow as 40 km beneath Adak Island (Fig. 2). As shown by Cross and Freymueller (2007), the western part of the Andreanof block is an area of strong interplate coupling. The enhanced coupling west of the Amlia fracture zone is manifest geomorphically by (1) the uplift of the outer-arc high, Hawley Ridge, and (2) the down-tilted summit platform, which is now located at a depth of ~1800 m (Figs. 1 and 6). The uplift of Hawley Ridge relative to other segments of the trench is not likely owing to locally greater amounts of sediment accretion because trench sediment thickness is modest. Trench sediment is actually thicker east of Amlia fracture zone, where the oldest Pacific plate is being subducted (Fig. 15). Instead, the ridge may be uplifting as the result of a combination of duplexing and along-arc translation of outer forearc and arc framework rock (Ryan and Scholl, 1989).

SUMMARY OF FOREARC BASIN EVOLUTION

Before the beginning of the Pliocene, the orientation of the Amlia fracture zone was similar to the relative plate motions between the Pacific and North American plate. Thus, the fracture zone migrated westward along the trench at a very low rate and was essentially in place for ~5 m.y. During early Pliocene time, the Amlia fracture zone migrated 33 km to the west along the Aleutian trench to arrive ~150 km east of its present location by the end of the early Pliocene (Fig. 12). Prior to the early Pliocene, no prominent forearc basin was present along the central Aleutian arc. The development of an outer-arc high that would create accommodation space for accumulation of basin sediment did not begin until the early Pliocene. In order to begin the formation of the Aleutian Terrace, the amount of sediment transported down the Aleutian Trench from the Gulf of Alaska needed to be sufficient to overtop the Amlia fracture zone and be accreted to the margin to form a small frontal prism (McCarthy and Scholl, 1985). The timing of the initial basin formation corresponds to the initiation of Alpine glaciation in the mountains surrounding the Gulf of Alaska at 5.5–6 Ma (Lagoe et al., 1993; Rea and Snoeckx, 1995) and subsequent arrival of significant amounts of sediment at the central Aleutian Trench. Elevated middle-series and Lower Pliocene strata at the seaward side of the forearc basin indicate uplift of the outer forearc possibly as early as late Miocene through early to middle Pliocene time (Figs. 8 and 9). The oldest forearc basin sediment was deposited closer to the trench within several small depocenters, with no evidence for a major basin depocenter west of Atka Island (Fig. 11). During the late Pliocene, deposition occurred within one prominent depocenter located beneath what is now Atka Basin (the forearc basin depocenter has migrated an unknown distance to the west since the late Pliocene). Late Pliocene forearc basin deposition was located further to the north in response to a growing outer-arc high; however, little sediment had yet accumulated in the forearc basin west of Atka Island (Fig.11).

Figure 15. Isopach map of sediment deposited on subducting Pacific plate. The thickest sediment in the trench is located immediately east of Amlia fracture zone (AFZ), where over 2 km of sediment have accumulated. Thickness is in meters assuming a sediment velocity of 2000 m/s. Interpretations are based on multichannel and single-channel seismic-reflection profiles available at http://walrus.wr.usgs.gov/NAMSS/.
Changes in forearc basin evolution occurred during the Quaternary. Relatively little sediment accumulated in the forearc basin during the early Pleistocene (Fig. 10). This could be the result of the lack of formation of accommodation space for forearc basin deposition. One possibility is that sediment from the Gulf of Alaska did not reach the central Aleutian Trench at this time, resulting in little accretion and uplift of the outer-arc high. Beginning in the early Pleistocene, the rate of the along-arc motion of the Amlia fracture zone increased, and the majority of the “bend” in the fracture zone was subducted (Fig. 12). The “bend” in the Amlia fracture zone entered the trench during the late Pleistocene, with anomaly 24.1 reaching the trench by 3.6 Ma (Fig. 12). We do not know the configuration of the bend of the Amlia fracture zone, but it is likely that the bathymetric expression of the fracture zone was complex and could have inhibited along-trench sediment transport. A paucity of trench sediment could have precluded continued development of accommodation space by uplift of the outer-arc high, resulting in no major accumulation of forearc basin sediment in the early Pleistocene (Fig. 11).

Major changes in the patterns of forearc basin deposition and deformation occurred in the past 1 m.y. or less. Hawley Ridge, a prominent outer-arc high, was uplifted with a forearc basin depocenter containing >1.4 km of sediment forming behind the ridge. East of Hawley Ridge, additional sediment accumulated beneath Atka Basin. The two depocenters are separated by a structural high, which formed as a result of shortening oriented perpendicular to the arc (Fig. 14). East of Atka Basin, the forearc basin has been inverted, with little remaining accommodation space. The outer forearc basin has been offset by strike-slip faulting along the Hawley Ridge shear zone, with the distal end of the forearc basin removed near the intersection of the forearc with the Amlia fracture zone (Fig. 7). These changes to the central Aleutian forearc are ascribed, in part, to a combination of (1) a decrease in the periodicity of glaciation known as the mid-Pleistocene transition (e.g., Clark et al., 2006), and (2) the subduction of the Amlia fracture zone, both of which affected sediment supply to the central Aleutian Trench.

Although an increase in ice-rafted debris at the beginning of the Quaternary signified an increase in glaciation in the Gulf of Alaska, the most significant intensification of glaciation did not begin until just ca. 1 Ma (Prueher and Rea, 2001). Millennial climatic oscillations resulted in multiple pulses of terrigenous sediment to the Gulf of Alaska as the result of more sustained sea-level lows (Rea and Snoeckx, 1995; Berger et al., 2008). Since the bend in the Amlia fracture zone had entirely subducted by 1 Ma, the topography associated with the subducting Amlia fracture zone is relatively simple and would not perhaps have formed a significant barrier to along-trench transport. Sufficient sediment was transported from the Gulf of Alaska down the Aleutian Trench axis to overtop the Amlia fracture zone barrier and smooth the rougher topography west of the Amlia fracture zone; over 1 km of trench sediment accumulated as far west as Adak Island (Fig. 15). Interplate coupling beneath the western Andreanof block may be enhanced by the smoothing of the subducting plate topography by sediment in the trench (e.g., Ruff, 1989). This enhanced coupling has resulted in shortening across the forearc basin and an increase in accommodation space. Since coupling is higher west of the Amlia fracture zone, whereas sediment in the trench is thicker east of Amlia fracture zone, the absolute amount of sediment deposited in the trench may not be as important to coupling as sufficient amounts of sediment (e.g., Heuret et al., 2012). In the area where the Amlia fracture zone is currently subducting, coupling is low despite the deposition of thick (>2 km) trench sediment. We suggest that a tear within the subducting Pacific plate along the Amlia fracture zone, allowing for trench rollback and the rotation of the eastern Andreanof block into the forearc, reduced the coupling beneath the eastern Andreanof block. As a result, the Aleutian Terrace in the eastern Andreanof is locally elevated and no longer accumulating a significant amount of forearc basin sediment.

### IMPLICATIONS FOR GREAT EARTHQUAKES

The area of thickest active forearc basin deposition and most accommodation space is near Hawley Ridge (Fig. 11). This area is also where the greatest amount of slip occurred during great megathrust earthquakes in 1957 and 1986 (Ryan and Scholl, 1993). The ability of this part of the forearc to store elastic strain implies that the forearc is stronger, perhaps owing to the over-riding plate being colder (away from slab tear) and composed of thickened arc framework rock. Plate coupling west of the Amlia fracture zone is enhanced by the shallower plate dip, resulting from at least partial decoupling of the slab across the slab tear, allowing greater buoyancy of the younger slab to the west. Conversely, the forearc east of Amlia fracture zone, which is not presently accumulating strain, may be weakened thermally near the slab tear from upwelling of asthenospheric material. Trench rollback, with concomitant upper-plate normal faulting, causes the terrain to collapse toward the trench, further decreasing arc coupling. Many studies have related the location of forearc basins to areas of high slip on the megathrust. However, features on the downgoing plate, which are translating parallel to the arc as the result of oblique subduction, can temporarily interrupt plate coupling. Thus, for example, the megathrust beneath the largest forearc basin in the central Aleutians, Atka Basin, is now accumulating little strain where the Amlia fracture zone is subducting (Freymueller et al., 2008).

One of the consequences of strong coupling and the rupture of great earthquakes is the triggering of very large massive mass transport deposits. Not only do mass transport deposits potentially provide a record of past great earthquakes, but also the thickness and scale of these deposits suggest that their failure could have been tsunamiogenic (e.g., Locat et al., 2004). Although we only have a few profiles that image the mass transport deposits, and they can be generated by a variety of mechanisms (e.g., Hampton et al., 1996), we do note that the majority of mass transport deposits occur within the forearc basin opposite where the summit platform has been cut back and eroded, suggesting removal of significant amounts of material (Fig. 1). It is therefore possible that a combination of dynamic loading during a great earthquake combined with a ready sediment source from the oversteepened and down-tilted summit platform created the conditions to generate these unusually thick mass transport deposits. Hypothetical submarine mass-flow tsunamis were modeled for the upper Aleutian trench slope and indicate that large transoceanic tsunamis can potentially be generated by failures such as these (Waythomas et al., 2009).

### CONCLUSIONS

Forearc basin sediment of the Andreanof block records significant tectonic processes that affect the central Aleutian arc. Chief among these is subduction of the Amlia fracture zone. Although the fracture zone is too small to cause substantial uplift and collapse of the forearc by its bathymetric relief alone, the contrasting interplate coupling controls the morphology of the forearc and outer-arc high, as well as sediment deposition patterns in the basin. As the fracture zone migrates along the oblique convergence margin, the outer forearc collapses extensionally in its wake, leaving a perched forearc basin with no remaining accommodation space. The strong coupling west of the fracture zone results in shortening of forearc strata, with ongoing deepening of the basin and increasing accommodation space. Climate also exerts an influence on strong coupling along the
megathrust in that sufficient sediment derived from continental glaciation must be transported down the Aleutian Trench to overtop the Amalia fracture zone and smooth the rough topography west of the fracture zone. As a result of the strong coupling west of the fracture zone, great tsunamiogenic earthquakes are generated, which can trigger the deposition of thick mass transport deposits in the forearc basin.

ACKNOWLEDGMENTS

We thank Lamont-Doherty Earth Observatory for use of the Ewing profile E904-1232 collected by chief scientists John Diebold and Sue McGary in 1992; these data are available through the academic seismic portal at the University of Texas Institute for Geophysics, http://www.ig.utexas.edu/sdc/. We thank Rob Harris at Oregon State University for directing us to the heat-flow data available for the central Aleutians. Discussions with Chris Nye, Steve Kirby, Nathan Bangs, and the U.S. Geological Survey Tsunami Source Working Group contributed to this study. We thank Nathan Bangs, Jeff Tropp, and Eric Geist for their reviews, which helped to improve the manuscript.

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Influence of the Amlia fracture zone on the evolution of the Aleutian Terrace forearc basin