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Crustal structure transition from oceanic arc to continental arc, eastern Aleutian Islands and Alaska Peninsula

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Abstract

The Aleutian island arc crosses from the Pacific Ocean to the North-American continent at the island of Unimak. 3-D finite-difference traveltime inversion of our onshore–offshore seismic reflection/refraction data gives a velocity model of the crust and uppermost mantle. The arc crust is on average 30 km thick, but thickens to almost 40 km under the western Alaska Peninsula. The transition from oceanic arc to continental arc is characterised by a decrease in average velocity in the upper crust from about 6.5 km/s to less than 6.0 km/s, with no systematic change in the velocity of the lower crust. Throughout our study area, in the upper 15 km of the crust the highest velocities are observed in the fore-arc just south of the volcanic line. In the lower crust, the lowest velocities of just 6.2 km/s are found close to the volcanic line. The uppermost mantle is quite heterogeneous with velocities ranging from 7.6 to 8.2 km/s, in part due to the thermal gradient from cold fore-arc to hot back-arc. Whereas the Aleutian oceanic (fore-)arc has higher seismic velocities than average continental crust throughout the crust, the Peninsula section is close to the continental average in the upper c. 20 km of the crust. We infer that repeated episodes of arc magmatism can produce a felsic-to-intermediate upper crust as is observed in the continents, but arc magmatism produces a thicker mafic lower crust than the average continent retains. Some of the excess mafic material in the island–arc crust can be attributed to pre-existing oceanic crust, which is less evident or absent in a continental arc.

Keywords: crust; velocity analysis; three-dimensional models; crustal thickening; Aleutian Islands; Alaska Peninsula

1. Introduction

Continents have grown since the Archean essentially by four processes [1,2]: arc magmatism, accretion of oceanic crust (ophiolites) and arc-related sediments at convergent plate boundaries, basaltic underplating of the crust, and plume-related intra-plate magmatism (hotspot magmatism).

We studied continental growth by arc magmatism at both an oceanic arc (formed on older oceanic crust) and a continental arc (formed on older continental crust) across the ocean–continent transition in the eastern Aleutian Islands and the western Alaska Peninsula. The Aleutian arc has a relatively simple tectonic history of c. 50 Ma of essentially stationary arc magmatism. It formed in Palaeocene or early Eocene time when

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the Bowers Ridge collided with the then active Beringian margin and subduction jumped to the present location of the Aleutian arc, trapping oceanic crust (Kula/Aleutia [3]) between the now inactive Beringian margin and the new arc [4]. The Aleutian arc intersects the Beringian margin at Unimak so that the Aleutian Islands west of Unimak (Fig. 1) form a mature oceanic island arc built on old oceanic crust, whereas the Alaska Peninsula and Shumagin Islands form a continental arc built on allochthonous terranes accreted to the North American margin, the Peninsular terrane on the Bering Sea side and the Chugach terrane on the Pacific side. The Peninsular terrane, accreted to North America in the Jurassic, comprises the early Jurassic Talkeetna oceanic arc intruded by the Middle Jurassic calc–alkalic Alaska–Aleutian Range batholith [5]. The Late Cretaceous and younger Chugach terrane (comprising Sanak and the outer Shumagin Islands at the eastern edge of our study area [6]) was accreted to the Peninsular terrane along the Border Ranges fault in the latest Cretaceous and early Tertiary [7,8].

Early geophysical work in the Aleutians [9–11] resulted in a simple crustal model [11] that persisted until 1994 with the publication of three-dimensional inversions (on c. 10 km grids) of earthquake arrival times [49] and our acquisition of new seismic reflection and refraction data [12–14]. The shallow structure of the arc was studied in the 1970s and 1980s with marine seismic and potential-field methods [15]. The EDGE profile through the northeastern Alaska Peninsula [16] provided a crustal transect to the east of our study area. Recent publication of wide-angle seismic observations in the eastern Aleutian Islands [13,14] includes detailed resolution tests and extensive model analyses. In contrast, in this paper, we focus on the oceanic arc–continental arc transition just east of the area described in those studies. We believe this is the first time that the seismic crustal structure of this particular tectonic setting has been investigated with the high resolution of controlled-source seismology.

Most petrologic models of island arcs imply that the bulk composition of arc crust is basaltic/gabbroic (48–52% SiO_2 for the high-Al basalt

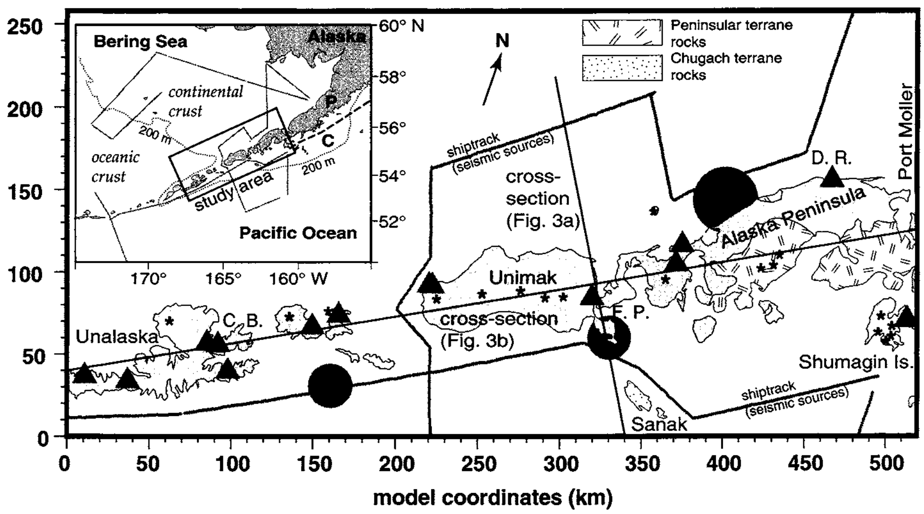

Fig. 1. Map view of the study area in southwestern Alaska, outlined in black on the inset map. Triangles mark receiver locations including C.B. Captains Bay, D.R. David River, F.P. False Pass. Grey lines mark shot locations (shiptrack). Grey circles O (oceanic Aleutian arc), C (continental Aleutian arc), and P (Alaska Peninsula) locate the velocity–depth functions in Fig. 6 averaged over the area of the circles. Dotted line on inset map marks 200 m isobath as proxy for continental–oceanic crust boundary. Long dashes on inset map mark the approximate location of the Border Ranges fault, the boundary between the Peninsular terrane (P) and the Chugach terrane (C) according to [33]. Exposures of Peninsular and Chugach terranes according to [6,33]. Volcanic and intrusive centres (asterisks) from [46].

samples in [17]); though arcs formed by slow subduction of hot oceanic crust may tend to bulk andesitic compositions [18]. Continental crust is in contrast believed to have intermediate (andesitic/dioritic) composition [19] with an SiO_2 content of 57% [20] to 63% [21]. A notable exception to the basaltic arc composition is the Izu–Ogasawara (Izu–Bonin) arc [22], which seems to have a continent-like andesitic bulk composition based on a seismic transect at 32°N [23,24]. We compare this model with our Aleutian results later in this paper. Different hypotheses to resolve the discrepancy between arc and continental composition have been evaluated in [25] in light of petrological and geochemical evidence whereas our paper concentrates on the seismological properties that

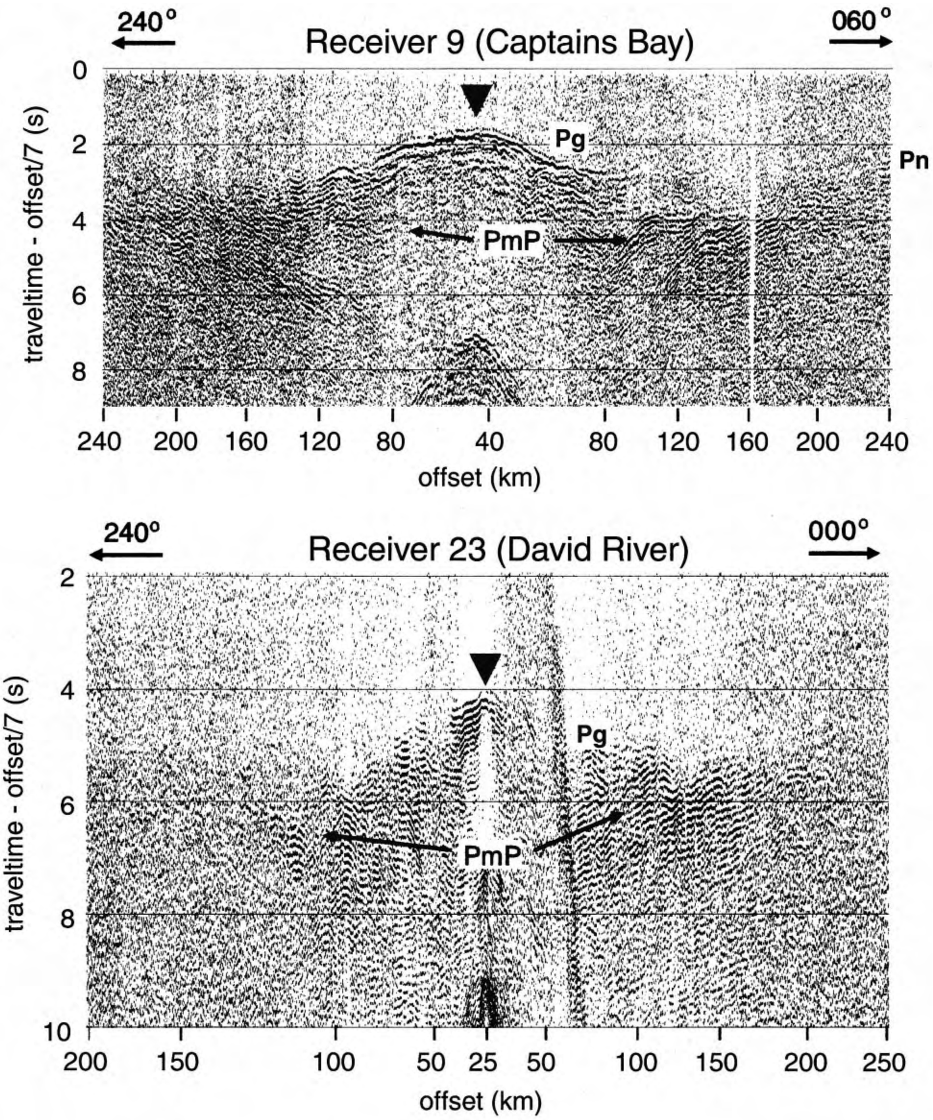

Fig. 2. Seismic receiver gathers of vertical component data from locations Captains Bay (C.B. in Fig. 1) and David River (D.R. in Fig. 1). Seismic phases at David River are delayed by c. 2 s and attenuated by young sediments of the Bristol Bay basin directly below the receiver.

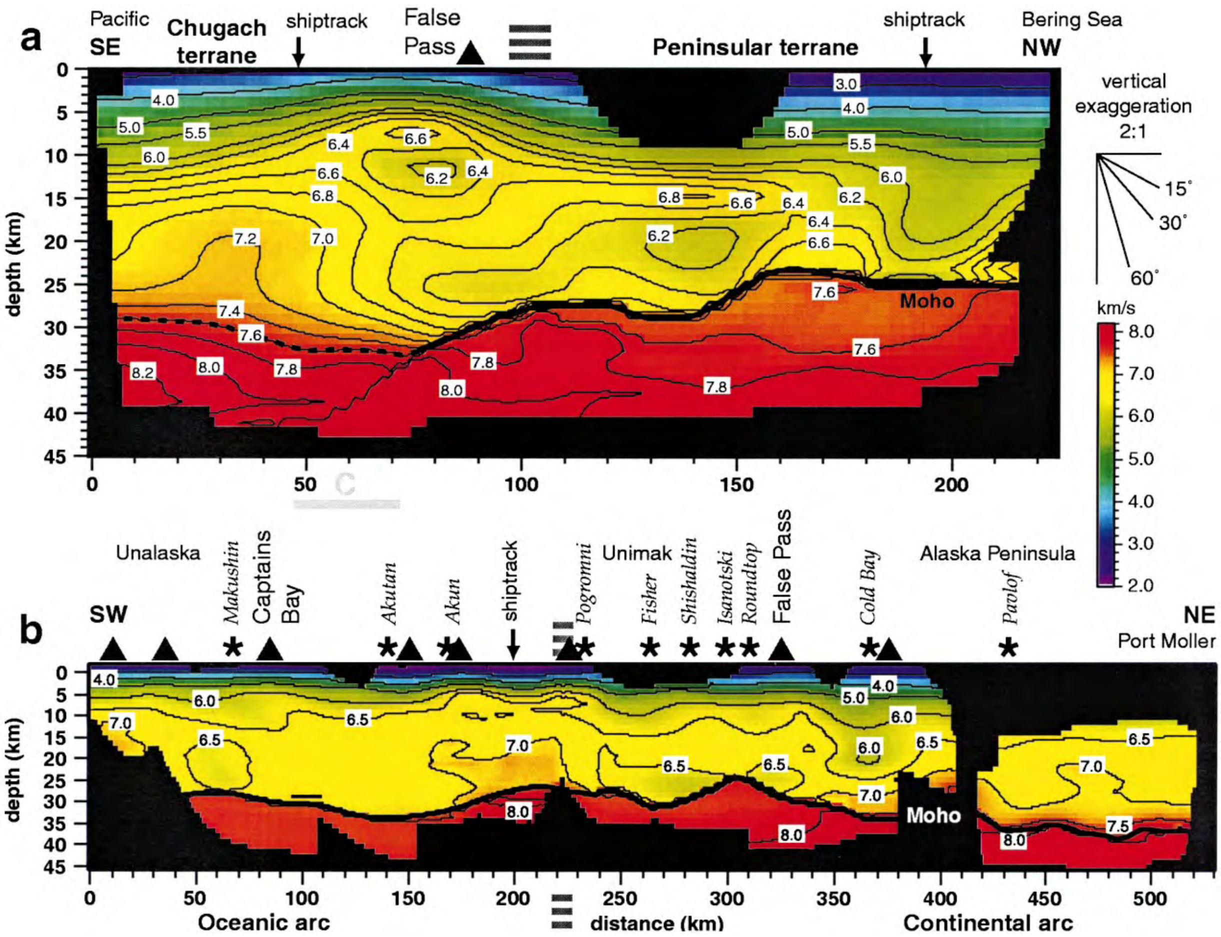

Fig. 3. Cross-sections through our 3-D velocity model, with a vertical exaggeration of 2:1 (for location see Fig. 1) intersecting near False Pass. Coloured areas are constrained by rays within a horizontal radius of 24 km. The Moho is shown by a solid black line, where constrained by nearby P_mP reflection points, dashed where determined solely by 7.6 km/s velocity contour. Triangles mark receiver locations near the cross-sections. (a) Arc-perpendicular section crossing the volcanic line near receiver station False Pass. Dashed grey vertical line marks the boundary between Chugach and Peninsular terranes inferred from mid-crustal velocities in Fig. 4. Light grey horizontal bar marks location of velocity–depth function C in Fig. 6. (b) Arc-parallel section along the line of active volcanic centres (asterisks, see Fig. 1). Dashed grey line marks the approximate boundary between oceanic arc and continental arc.

distinguish arc crust from average continental crust.

2. Wide-angle seismic measurements in the eastern Aleutians

Wide-angle seismic fan data were recorded by a deployment of IRIS/PASSCAL portable seismometers during a marine multichannel seismic reflection survey of the eastern Aleutian arc and the southern Bering shelf in 1994 (inset to Fig. 1) described in detail elsewhere [12–14,26]. Example receiver gathers (Fig. 2) from Captains Bay on Unalaska and David River on the Bering Sea coast of the Alaska Peninsula show typical data: first arrivals from crust (P_g) and upper mantle (P_n), reflections from within the middle to lower crust and the Moho (P_mP), and corresponding S-wave arrivals. (Crustal models west of Unimak and additional receiver gathers are discussed in [13]). All the data are freely available from http://www.iris.washington.edu/. The following models are based on traveltime picks of the P_g, P_n, and P_mP arrivals from the land receivers recording airgun shots within the model area outlined on the inset map in Fig. 1. We used a 3-D finite difference code to model the picked traveltimes and invert for velocity [27–29]. This procedure allows us to do tomography on a densely sampled velocity model (with node-spacing 1.2 km) with both refracted and reflected arrivals. We used refracted (first) arrivals to invert for velocity only, and reflected arrivals from the Moho (P_mP) to invert both for velocity and depth to the reflecting interface, following [29]. Three slices through the final 3-D velocity model are displayed: two vertical cross-sections, perpendicular to the arc through False Pass (Fig. 3a), and along the volcanic line of the arc (Fig. 3b), and one horizontal slice through the upper crust at 10.2 km depth (Fig. 4). Synthetic resolution tests for the partially overlapping model in [13] suggest velocities are accurate to about ±0.2 km/s. Where the two models overlap, the model of [13] has been kept as it results from additional constraints outside the boundaries of this study.

3. Seismic structure of the eastern Aleutians

Since the land receivers mainly recorded long offsets (minimum offset 20 km, maximum offset with useful signal c. 350 km), reflected arrivals from the lower crust and upper mantle are predominant in the gathers (Fig. 2). Usually the Moho is the main reflector that can be observed (P_mP) in the recorded offset range. But in the eastern Aleutian Islands this reflection often does not stand out clearly from shallower (lower-crustal) and deeper (upper-mantle) reflectivity. Both gathers shown in Fig. 2 (and additional gathers shown in [13]) are characterised by fuzzy reflectivity looking westwards (towards the island chain) and well-defined reflectors looking east- and northwards (towards the Alaska Peninsula and the Bering Sea).

P_mP picks are more numerous and reliable in the back-arc than in the fore-arc where we have to rely mainly on the velocities to define the Moho

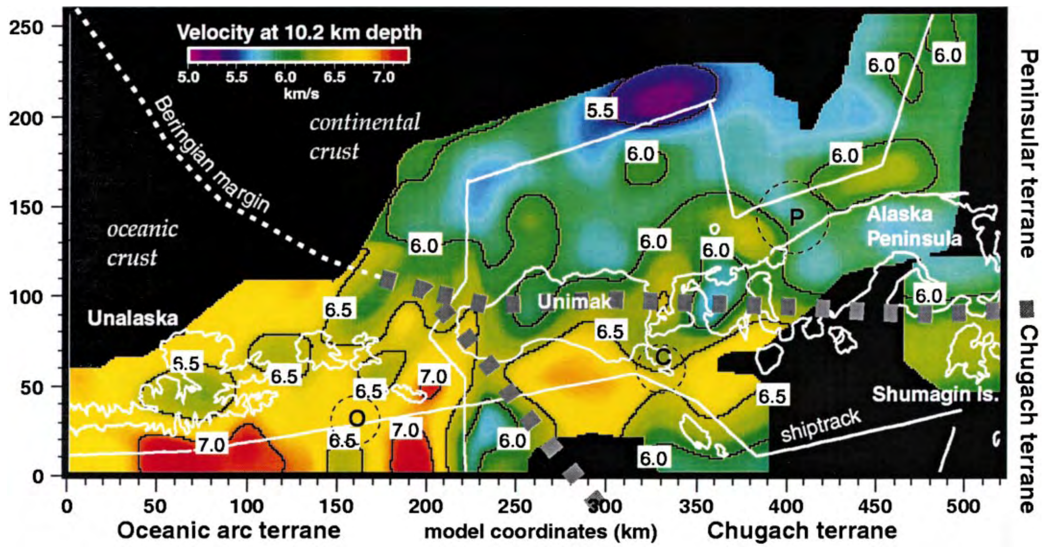

Fig. 4. Horizontal slice (same area as Fig. 1) through our 3-D velocity model at 10.2 km depth. Coloured area as in Fig. 3. Shiptrack (shot points) and coast lines are outlined in white. The Beringian margin (white dashes) is drawn along the 400 m isobath. Velocity depth functions O, C and P in Fig. 6 are shown as dashed circles. Dashed grey lines mark terrane boundaries based on the seismic velocity distribution.

(conventionally set to coincide with the 7.6 km/s contour [30]; Fig. 3a). The crust is typically thickest just in front of the volcanic line (Fig. 3a) with Moho depth varying from c. 25–30 km beneath the Aleutian Islands to up to 40 km beneath the Alaska Peninsula (Fig. 3b).

Systematic crustal velocity variations along the arc are hard to discern apart from a general decrease from west to east (Fig. 3b). We observe no correlation of velocity anomalies with individual, active volcanic centres, presumably due to the large spacing of our seismic receivers: with a typical receiver spacing of 50 km, anomalies smaller than 50 km are not mapped correctly if detected at all (see detailed discussion of seismic resolution in [13]). Zones of low velocity are especially difficult to resolve because seismic rays preferentially travel through zones of high velocity and no turning rays (which provide the best constraints on velocity at the turning point) emerge from low-velocity zones (turning rays require an increase of velocity with depth). It is therefore not possible to associate the narrow velocity depressions below Makushin and Cold Bay (Fig. 3b) with the magmatic activity of these volcanic complexes. On the other hand, it is quite probable that the longer-wavelength decrease in crustal and upper-mantle velocities from Akun to Unimak (Fig. 3b) is real and in part reflects elevated temperatures under the more active Unimak volcanos (especially Shishaldin [31]). A decrease of 0.2 km/s in V_p for gabbro corresponds to a temperature increase of 350°C, roughly the temperature difference between an average- and a high-heat-flow province at 30 km depth [32]; but it is unlikely that strong horizontal temperature gradients can be maintained for a long time so compositional differences must play a role as well. We have chosen not to smooth our final velocity model back to our formal resolution limits because that would not represent a more correct image, and would give a probably false impression of homogeneity. Instead, we discuss in Section 4 1-D velocity–depth curves which are either taken from areas in the model that are better constrained than the rest (showing local structure where it can be resolved) or are averaged over a wide area (showing therefore no local structure, just bulk averages).

Both crustal and upper-mantle velocities decrease from the fore-arc (Pacific) to the back-arc (Bering Sea) with a local upper-crustal minimum close to the volcanic line (Fig. 3a). The upper-crustal minimum could indicate a zone of partial melting, containing magma chambers that feed the Unimak volcanic centres, but the size of the anomaly is at our resolution limit (a specific magma chamber would probably be too small to resolve). The general velocity trend is also visible in the horizontal slice through the upper crust (Fig. 4); velocities range from 6 to 7 km/s in the south but are less than 6 km/s north of the arc. The projection of the Bering shelf margin into the arc–continental crust on Unimak divides these two domains between the 6.0 and 6.5 km/s velocity contours. This line and a north–south trending trough of velocities < 6 km/s south of western Unimak divide the upper crust into three seismically distinct regions which we infer represent the three distinct terranes that make up our area (oceanic Aleutian arc, continental Peninsular and Chugach terranes). We associate the low velocities in the north with Peninsular terrane basement such as exposed at location P and the eastern end of cross-section Fig. 3b. We associate intermediate velocities in the southeast with the Chugach terrane exposed in Sanak and the outer Shumagin Islands [6,33]. Though the boundary between the Peninsular and Chugach terranes is not exposed in our area, our inferred boundary is consistent with the location of the north-dipping Border Ranges thrust fault east of our study area (inset to Fig. 1; note that [6] draws the fault farther south thereby including the inner Shumagins in the Peninsular terrane). The Moho step up from c. 30 to c. 25 km depth (Fig. 3a, 150 km) may be related to this suture zone. We associate the variable, but generally high velocities in the southwest (Fig. 4) with the Aleutian oceanic arc terrane.

4. Comparison with other arc and continental crust

There are too few similar studies available from other island arcs to know whether our study of the Aleutian arc is representative of island arcs in

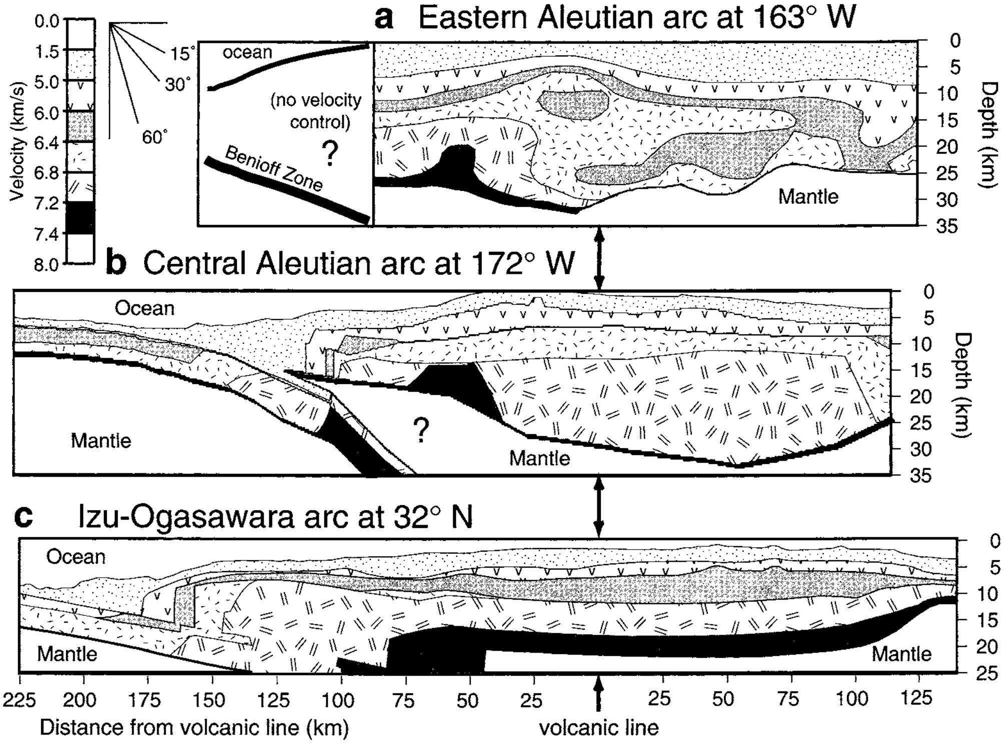

Fig. 5. Three arc cross-sections aligned along the volcanic line, back-arc to the left and fore-arc to the right, 2:1 vertical exaggeration: (a) this study (Fig. 3a). (b) Aleutian arc 350 km west of our study area from [14]. (c) Izu–Ogasawara arc (Japan) from [23].

general. Fig. 5 compares our cross-section Fig. 3a (redrawn as Fig. 5a) with a cross-section through the central Aleutian arc (Fig. 5b, after [14]), acquired as part of our overall experiment [12–14,26] and with a cross-section through the Izu–Ogasawara (Izu–Bonin) arc (Fig. 5c, after [23]). Fig. 5b,c is based on ocean-bottom seismometer recordings across the arcs from the trench to the back-arc. The Izu–Ogasawara arc is wider than the central Aleutian arc (probably due to the shallower subduction angle), but considerably thinner than the central or eastern Aleutian arc. The thickness difference may be attributable to the age difference between Izu–Ogasawara (48 Ma) and the Aleutians (55 Ma [7]) and to the multiple episodes of rifting within the Izu–Ogasawara arc [34]. The internal differences are striking. Izu–Ogasawara has a mid-crustal layer of 6.0–6.4 km/s, implying a granitic to dioritic composition, that is also present in the eastern Aleutian continental back-arc, but largely absent in the central, oceanic Aleutians and in the eastern Aleutian fore-arc. Instead, the oceanic Aleutian middle crust typically has velocities of 6.4–6.8 km/s, locally even 7.2 km/s (location O in Figs. 4 and 6), which implies a more gabbroic composition. In all three cross-sections the bulk of the lower crust has velocities of 6.8–7.2 km/s, though decreasing in the Aleutian back-arc, particularly in the eastern, continental section. Within island arcs a substantial crustal layer with velocities of 7.2–7.4 km/s is known only from Izu–Ogasawara. Since no common lithologies have these velocities (except partially eclogitised gabbros and partially molten ultramafics), this layer suggests a gradational boundary between crust and mantle. A higher proportion of mantle rocks will push the seismic velocities eventually into the mantle domain (defined as >7.6 km/s [30]) as possibly evidenced in the eastern Aleutians. The thick zone of near-

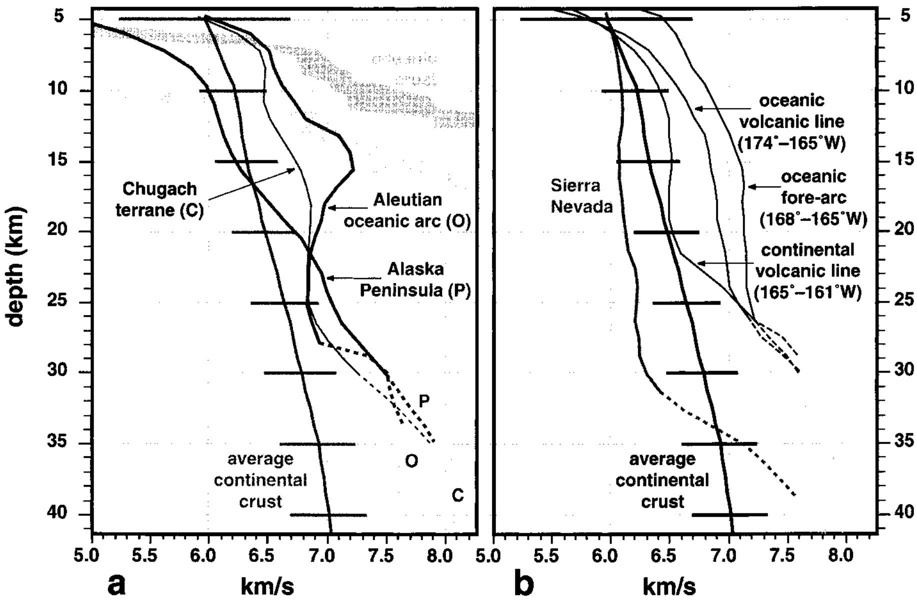

Fig. 6. Comparison of arc velocity–depth functions with the velocity–depth function of average continental crust [32], modified from [47] (for analogous curves relating to Fig. 5b see [14]). Horizontal bars are 1σ uncertainties of the continental curve. Dashed curves are the transitions from crust (dark grey and black) to mantle (light greys).(a) Three velocity–depth curves from the best constrained parts of each of the terranes in this study (for locations see Figs. 1 and 4): curve O from the oceanic fore-arc near the ocean–continent boundary, curve C from near the volcanic line in the Chugach terrane, curve P from the back-arc on the Alaska Peninsula in the Peninsular terrane. The dark grey area shows the range of oceanic crustal velocities [48] assuming 5 km water depth; the light grey area shows the same range buried 4 km deeper. (b) Averaged velocity–depth curves from the Aleutians ([13] and this study), and from the continental southern Sierra Nevada of California [38,47]. The fore-arc curve averages the island fore-arc south of Unalaska eastwards up to the location of curve O (part of the reflector line in [13]); the oceanic volcanic line curve averages the volcanic line (receiver line profile in [13]) from 174 °W to west of Unimak; and the continental volcanic line curve averages the volcanic line from Unimak to the eastern end of our velocity model at Port Moller on the Alaska Peninsula.

Moho velocities below the Moho in the back-arc (Fig. 3a) may be equivalent to the Border Ranges Mafic–Ultramafic Complex of the Peninsular terrane exposed further east along the Border Ranges fault [35]. Both in the Izu–Ogasawara [24] and the eastern Aleutian arcs, the Moho also disappears as a sharp, reflective boundary in the fore-arc.

In summary, while the Aleutian island arc shows great internal variability, its overall higher seismic velocities especially in the middle crust distinguish it clearly from the Izu–Ogasawara arc which is more continental in character. Only where the Aleutian arc is built on older accreted terranes in the back-arc region does its crustal structure become more like Izu–Ogasawara. The fore-arc (inboard of the accretionary prism) in all three cross-sections shows higher seismic velocities (more mafic composition) than is typical of continental crust. We may speculate that the appearance of ‘continental’ seismic velocities in arcs results from either multiple accretionary/arc-magmatic episodes (eastern Aleutian arc) or multiple arc-rifting episodes (Izu–Ogasawara arc).

For the purpose of this study, the best available model of average continental crust is one based on seismic velocities [32] (Fig. 6). Because of the internal variability even within our restricted study area, any single velocity–depth curve for the Aleutian arc may be misleading. We therefore compare several curves that highlight different aspects and regions of the Aleutian arc. The curves in Fig. 6a are taken from the three terranes in the eastern Aleutians, in locations where ray-coverage and therefore velocity resolution is good throughout the crust (we exclude the uppermost 5 km of the crust from our display, following [32]). The curves in Fig. 6b average over larger areas, including [13]. Although seemingly more representative of the arc as a whole, they have the disadvantage of averaging across areas of varying ray-coverage (and therefore changing reliability of the velocities) and varying structure (producing meaningless intermediate velocities where the depth of the boundary between distinct layers, e.g. crust and mantle, changes).

The oceanic fore-arc (Fig. 6 curve O) shows crust with substantially higher velocities for most of the crust (more mafic composition) than the continental average, particularly in the middle crust at 15 km depth, which is very similar to typical oceanic crust (gabbroic layer 3) buried by about 10 km of continental crust. This quasi-oceanic layer is absent from curve C where the arc is built not on oceanic crust, but on the accreted Chugach terrane. This distinction is not unequivocal: Fig. 3a shows indications of a similar layer at the eastern end of Unimak (velocity >6.6 km/s); and the continuity of the quasi-oceanic layer west of Unalaska [13] is at best uncertain. However, an alternative interpretation as individual mafic intrusions seems less plausible due to the large extent of the observed velocity anomaly. The existence of a high-velocity, quasi-oceanic middle crust would suggest that the pre-existing oceanic crust has not yet been completely assimilated by arc magmatism, but rather acted as a density filter that separated the felsic-to-intermediate fraction of arc magmas from the mafic residue that accumulated in the lower crust [36,37].

In contrast to oceanic–arc curve O, the Peninsular curve P is much closer to an average continental function although it has a higher velocity gradient so that its lowermost crust has higher velocities than the oceanic–arc curve O. Part of the difference is probably due to temperature differences: the oceanic–arc curve comes from close to Akutan, one of the most active volcanos in the Aleutian chain, whereas the western Alaska Peninsula is less volcanically active. The continental arc (Chugach terrane) curve C generally has velocities between the extremes, but it follows the oceanic–arc trend more closely than the Peninsular trend and is indeed close to the average along the oceanic volcanic line (Fig. 6b) of the entire sector of the eastern Aleutian arc investigated here and in [13]. Averaged along 700 km of arc, the oceanic volcanic line has velocities 1–2 standard deviations higher than average continental crust, even though the velocity gradient is similar. In contrast, the continental section of the volcanic line alone (Unimak and Alaska Peninsula) has velocities that are lower, within 1σ of average continental crust, whereas the average fore-arc velocity is 0.3 km/s faster and exceeds average continental velocities by 2σ (Fig. 6b).

The average crustal velocity for the eastern Aleutian fore-arc is 6.86 km/s (all averages are over velocities <7.6 km/s in accordance with [32]); from 5 to 15 km depth velocities increase from 6.4 to 7.1 km/s and remain nearly constant below that. This implies a bulk composition of mafic granulite or amphibolite with the gradient zone ranging from diorite to gabbro and the lower crust consisting of gabbro or mafic garnet granulite (all conversions are based on the compilation in [32] under the assumption of an average continental geotherm). The oceanic volcanic line average is 6.56 km/s implying a bulk composition between diorite and mafic granulite, but permitting a range of specific compositions from granite to gabbro. At least part of the difference between fore-arc and volcanic line must be due to higher temperatures in the volcanic line so that the true composition for the island arc as a whole lies between the two [13]. We have excluded extrusive rocks, which have considerably lower seismic velocities than their intrusive equivalents. The only extrusive rock that matches our velocities at 5 km depth is basalt, but the velocity gradient in the uppermost crust is steep, so that more felsic rocks are expected to be a major component at shallow depths. Finally, the continental arc velocities (especially of the Alaska Peninsula) are compatible with continental velocities except for the lowermost crust: the continental volcanic line average is 6.44 km/s barely different from the continental average of 6.45 km/s [32].

From Fig. 5 it appears that the Aleutian oceanic arc represents a mafic end-member of arc compositions, whereas the continental Aleutian arc tends to a more intermediate, continent-like composition. There exist yet more felsic arcs with velocities about 1σ below the continental average, such as the Sierra Nevada continental arc in California (Fig. 6b), though the comparison is difficult since the Sierra Nevada is incomplete and inactive [38]. The Izu–Ogasawara arc lies between these extremes with middle crustal velocities similar to the Sierra Nevada, lower crustal velocities similar to the Aleutians and an overall composition estimated to be similar to average continental crust [22].

5. Transformation of arc crust into average continental crust

Subduction-related, mantle-derived basaltic magmas only result in a felsic addition to the upper crust if they add substantial mafic material to the lower crust. It has been estimated [39] that for every unit of upper crustal, andesitic magma generated from a primitive basaltic liquid, 1.3 units of fractionated mafic residue remain in the lower crust or are added as ultramafic cumulates to the base of the crust in the seismic mantle. A somewhat smaller proportion of mafic lower crust (0.7–1.0) is implied by seismic velocities of the Aleutian arc [13] and the world-wide average for arcs [40]; these estimates exclude ultramafic cumulates which are not part of the seismic crust. This reasoning obviously does not apply where the primary magma is already andesitic (see e.g. [41] for the Komandorsky region of the westernmost Aleutians where relative plate motion is approximately strike-slip and [18] for southwestern Japan where young, hot lithosphere is subducted).

In order to convert arc crust as observed in the Aleutian island arc into average continental crust, felsic material must be created by melt fractionation in the upper crust, and surplus mafic residue must be removed from the lower crust. A possible process is delamination of the lower crust as it undergoes a phase change from gabbro to denser eclogite [42]. An extreme example of that process has been observed in the Sierra Nevada of California [38,43], perhaps the seismically best-characterised continental arc; its velocity profile (Fig. 6b) indicates a felsic (granodioritic/tonalitic) composition of the entire crust similar to that of the Izu–Ogasawara arc middle crust implying that the counterpart mafic root has been removed [44].

The most basic observation from the Sierra Nevada and Aleutian arcs, the average velocity–depth profiles, show a dramatic difference between the two types of crust and also roughly bracket the range of velocity–depth functions observed in continents world-wide. The velocity–depth function of the Sierra Nevada batholith is about 1σ below, and the Aleutian island arc 1σ above the average continental velocity–depth function. Almost the entire Aleutian crust (everything below c. 7 km depth) is mafic and could therefore be considered 'lower (continental) crust', even if one discounts the highest velocities in the mid-crust (12–18 km depth) as pre-existing oceanic crust (i.e. it is not added to the crustal column by arc magmatism, but it would add to the continental crust after suturing). Although in comparing the velocity–depth functions of the two arcs, one has to be careful to take into account the exhumation level of the Sierra Nevada batholith (c. 10 km in the observation area; [45]), correcting for erosion by moving the Sierra Nevada curve in Fig. 6b 10 km deeper increases the differences that must be explained. It is clear that the first-order difference between the Sierra Nevada continental arc and the Aleutian island arc is the more felsic composition of the continental arc, the entire crust of which has a velocity of 6.0–6.3 km/s.

On the other hand, the Aleutian arc is much more heterogeneous in its seismic structure than the Sierra Nevada: the same subduction process has affected the pre-existing lithosphere of different origin along the arc. The Aleutian arc crust is most continent-like where the pre-existing crust consists of previously accreted arc terranes. The older Peninsular terrane, which encompasses the volcanic line and back-arc in the eastern half of our study area, had already experienced several episodes of arc magmatism when the Aleutian arc formed. The resulting crustal column is continent-like. The fore-arc, built on the younger Chugach terrane, retains the high-velocity characteristics of the island arc section. Repeated cycles of arc magmatism have in the end produced a 'average continental crust'. It is not obvious whether this is achieved by reworking of the entire pre-existing arc crust or by addition of felsic material to the upper and middle crust and partial removal of the mafic lower crust. The continental Aleutian back-arc has unusually low upper-mantle velocities (7.6 km/s; Fig. 3a). The back-arc crust together with this upper-mantle layer is just as thick as the high-velocity fore-arc. This observation may indicate that indeed part of a former mafic lower arc crust is transforming into eclogite (seismic mantle) or that pyroxenite-rich ultramafic cumulates (the seismic velocity of pyroxenite is about 7.6 km/s for an average geotherm) balance the felsic crustal section in the upper mantle. Seismic velocities alone cannot resolve these ambiguities.

6. Conclusion

The section of the eastern Aleutian arc studied in this paper can be divided roughly into three parts: an oceanic–arc section in the west (the islands Unalaska, Akutan and Akun) and a continental arc section in the east (the island Unimak, the Shumagin Islands and the western most Alaska Peninsula), which is subdivided into a fore-arc section (Shumagins, southern half of Unimak and the Pacific shelf) and a back-arc section (northern half of Unimak, the Alaska Peninsula and the Bering shelf). The oceanic–arc and continental fore-arc sections have a thick high-velocity lower-crustal section (6.8–7.2 km/s), whereas the back-arc shows more intermediate velocities (6.0–6.8 km/s). A similar variability is seen along the arc with crustal velocities decreasing in general from west to east. The implied composition of the fore-arc is considerably more mafic than average continental crust, whereas the continental back-arc is indistinguishable from continental crust. Some of the velocity decrease from fore-arc to back-arc can be attributed to a higher geothermal gradient, but part of the difference must be compositional. Since the continental Aleutian arc intruded pre-existing arc crust, the higher-velocity mafic island fore-arc is probably more representative for the pure Aleutian arc contribution to crustal growth. Reworking of older arc crust subsequently leads to the creation of more felsic material within the crust resulting in a continental crustal column.

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