

Structure and composition of the Aleutian island arc and implications for continental crustal growth

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ABSTRACT

We present results of a seismic reflection and refraction investigation of the Aleutian island arc, designed to test the hypothesis that volcanic arcs constitute the building blocks of continental crust. The Aleutian arc has the requisite thickness (30 km) to build continental crust, but it differs strongly from continental crust in its composition and reflectivity structure. Seismic velocities and the compositions of erupted lavas suggest that the Aleutian crust has a mafic bulk composition, in contrast to the andesitic bulk composition of continents. The silicic upper crust and reflective lower crust that are characteristic of continental crust are conspicuously lacking in the Aleutian intraoceanic arc. Therefore, if island arcs form a significant source of continental crust, the bulk properties of arc crust must be substantially modified during or after accretion to a continental margin. The pervasive deformation, intracrustal melting, and delamination of mafic to ultramafic residuum necessary to transform arc crust into mature continental crust probably occur during arc-continent collision or through subsequent establishment of a continental arc. The volume of crust created along the arc exceeds that estimated by previous workers by about a factor of two.

INTRODUCTION

Understanding the origin of continental crust is hampered by our limited knowledge of the composition and structure of island arcs, which have been proposed as a principal site of crustal genesis at least throughout the Phanerozoic, and perhaps longer. Two decades ago, Taylor and McLennan (McLennan and Taylor, 1982; Taylor, 1977; Taylor and McLennan, 1981) proposed the “andesite model” of continental crustal growth, which holds that arcs produce crust of bulk andesitic composition, in accord with the andesitic bulk composition of continental crust (Christensen and Mooney, 1995; Rudnick and Fountain, 1995). Growing evidence, however, indicates that the bulk composition of island arcs is closer to basalt than to andesite, thus posing an apparent paradox in the “island arc” model of continental crustal growth (e.g., Kay and Kay, 1986; Smithson et al., 1981). Delamination of mafic and ultramafic lower crust has been proposed as a possible solution to this paradox. Alternatively, Kelemen (1995) has proposed that island-arc crust may contain a substantial proportion of andesites with high Mg/(Mg + Fe) composition.

In order to test such models of continental crustal formation, we need improved understand-

ing of the composition and rates of magmatic production of island arcs. Geophysical data provide key constraints by providing estimates of magma volumes and a basis for comparing properties of island arcs and continental crust. In this paper we present a new seismic velocity model of the Aleutian island arc, based on seismic data acquired in 1994. Our results show that, although the volume of crust created in the Aleutian island arc is greater than previously supposed, the seismically inferred composition and reflectivity of that crust are unlike those of mature continental crust, implying that, if island-arc crust forms a significant portion of continental crust, it must be substantially modified during or after accretion to a continental margin.

GEOLOGIC SETTING AND SEISMIC EXPERIMENT

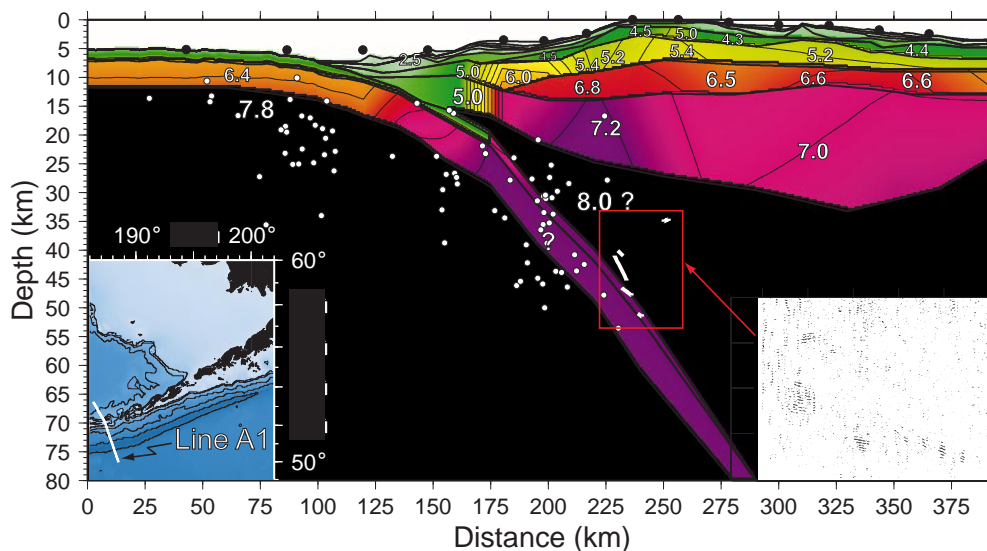
The Aleutian island arc, which is the result of northwestward subduction of the Pacific plate beneath the North American plate, formed in the early Eocene (55–50 Ma), probably in response to buckling of the Kula plate (Scholl et al., 1987). Reflection seismic and mapping data indicate that basement rocks of the Aleutian morphologic ridge comprise three stratigraphic units, an

Eocene lower sequence of volcanic rocks, an Oligocene to Miocene middle sequence of marine sedimentary rocks, and a Pliocene and Quaternary upper sequence of sedimentary and igneous rocks (Scholl et al., 1987). Magmatism waxed and waned over time (Fournelle et al., 1994), with a major arc-building episode in the Eocene and a concentration of magmatic activity to form summit volcanoes ca. 40 Ma (Scholl et al., 1987). The arc is structurally segmented into blocks that have undergone clockwise rotation (Geist et al., 1988). Aleutian arc lavas range in composition from basalt to dacite, with rare rhyolite (Fournelle et al., 1994; Kay et al., 1982), but the dominant lava is basaltic (Myers, 1988). A geophysical study by Grow (1973) found a crust of maximum 25 km thickness and a volume of about 2300 km³ per kilometer of arc.

The data reported in this paper were acquired in 1994 during a two-ship seismic reflection and refraction survey. Shots fired by the 20-element airgun array of the R/V *Maurice Ewing* were recorded at near-vertical incidence on a 4-km multi-channel hydrophone streamer on the *Maurice Ewing* and at farther offsets on ocean-bottom instruments (Woods Hole Oceanographic Institution hydrophones and U.S. Geological Survey

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Figure 1. P-wave velocity model of lithosphere along Aleutian island-arc profile A1 (white line, lower left inset). Velocities (white numbers) are contoured every 0.2 km/s from 5.0 to 7.2 km/s. White circles are earthquake hypocenters, from database provided by R. Engdahl, U.S. Geological Survey; only those hypocenters are plotted that lie within 125 km to west of line A1 and have hypocentral depth-determination errors <4 km. Black circles show locations of ocean-bottom seismic instruments on which wide-angle data were recorded. Lower right inset shows part of stacked, multichannel seismic (MCS) reflection data on profile A1, extending 25 km horizontally and from 9 to 17 s two-way traveltime. Red box shows approximate region covered by MCS data in inset; bold white lines show migrated positions of several prominent events in MCS data.



seismometers) deployed from the R/V *Alpha Helix* and on portable seismometers deployed on Aleutian islands (Fliedner and Klemperer, 1998). One along-arc and two arc-crossing profiles were recorded. In this paper we present the P-wave velocity structure of the island arc along profile A1, which crosses the island arc in Segum Pass, between Segum and Amlia Islands (Fig. 1).

VELOCITY MODEL AND CRUSTAL COMPOSITION

The P-wave velocity model shown in Figure 1 was derived by travelt ime inversion (Zelt and Smith, 1992) of wide-angle reflections and refractions recorded on ocean-bottom instruments on line A1.¹ Velocities in the arc are constrained by intracrustal refractions and reflections observed on 10 instruments. In addition, the structures of the forearc and backarc basins were constrained by reflections on the stacked multichannel seismic (MCS) section (Bangs et al., 1995). Wide-angle Moho reflections from the arc were observed on six instruments, at offsets as great as 180 km. We estimate uncertainty in average velocities within crustal layers to be ± 0.1 km/s in the upper crust and ± 0.15 km/s in the middle and lower crust.

The principal features of the Aleutian arc velocity structure are (1) a crustal thickness of 25–30 km beneath the arc and most of the backarc; (2) two upper crustal layers of relatively low velocity (4.3–5.0 km/s and 5.2–5.4 km/s) beneath a drape of volcanoclastic sediments; (3) a mid-crustal layer with a thickness of 3–6 km and a velocity of 6.5–6.8 km/s; and (4) a lower crust of variable thickness (10–20 km) and velocity (6.9–7.3 km/s). Several aspects of the model are remarkable, including the relatively thick crust

that continues 100 km behind the arc, and a subducting slab that is only 50–60 km beneath the present-day arc platform. In addition, one feature is notably absent: there is virtually no material within the arc with velocities of 6.0 ± 0.4 km/s. This finding is in marked contrast to recent results from the Isu-Ogasawara arc (Suyehiro et al., 1996) and to the velocity structure of continental crust, as we discuss in the following.

The interpretation of composition from seismic P-wave velocity is nonunique and affected by numerous factors such as pressure, temperature, and porosity. Nonetheless, given constraints on pressure and temperature and some reasonable assumptions, P-wave velocities can provide insight into crustal composition. In the upper 7 km of the crust, velocities of 4.3–5.4 km/s are too low to correspond to crystalline rocks and thus indicate fractured, porous, or altered rock. On the basis of exposed geology, we interpret the upper crust to consist largely of extrusive and intrusive igneous rocks of varying composition, and some volcanoclastic sediments. The boundary between layers with velocities of 4.3–5.0 km/s and 5.2–5.4 km/s may represent a downward increase in the abundance of plutons or increasing compaction of extrusive rocks. Despite the compositional variability of igneous rocks in the Aleutians, the predominant lava types are basalt and basaltic andesite (e.g., Myers, 1988); therefore we assign this layer a bulk composition intermediate between basalt and basaltic andesite.

Two interpretations of the mid-crustal layer (6.5–6.8 km/s) are possible. First, the layer may represent arc-related intrusions, perhaps at a level from which mid-crustal magma chambers fed surface eruptions. The velocity of 6.5–6.8 km/s, at 3–4 kbar confining pressure, would be consistent with intermediate (andesitic) compositions (e.g., Holbrook et al., 1992). A second possibility is that the layer represents a remnant of the Kula plate oceanic crust on which the island arc was originally built. This interpretation is supported

by (1) the rough similarity in thickness and P-wave velocity of this layer and the Pacific oceanic crust south of model km 100 and (2) the continuation of the layer to the north end of the model, at a depth at which oceanic crust of the backarc must eventually appear. Although our survey did not extend far enough to confirm the continuity of the mid-crustal layer farther into the backarc, we tentatively interpret this layer as a thinned, intruded remnant of Kula plate oceanic crust. In this case, the bulk composition of the layer would presumably be that of mid-ocean ridge basalt (MORB).

Velocities of 6.9–7.3 km/s in the thick lower crust are indicative of a mafic bulk composition (Christensen and Mooney, 1995; Holbrook et al., 1992). Two candidate compositions for the lower crust (Kay and Kay, 1985) are the mafic residua of either calc-alkalic fractionation (43.2 wt% SiO_2 , 13.2% MgO) or tholeiitic fractionation (47.9% SiO_2 , 12.5% MgO). We can test the appropriateness of these compositions by using the empirical velocity-composition relationship of Kelemen and Holbrook (1995), $V_p = 8.054 - 0.024(\text{SiO}_2) + 0.029(\text{MgO})$, where SiO_2 and MgO are oxide compositions in weight percent. The predicted velocities (at 4 kbar pressure and 25 °C) of the calc-alkalic and tholeiitic residua are 7.4 km/s and 7.3 km/s, respectively, which correspond to about 7.1 km/s and 7.0 km/s at in situ temperatures, in good agreement with observed lower crustal velocities. These mafic residua, combined with intruded primary melts of mafic composition, are thus likely constituents of the lower crust.

Subcrustal velocities beneath the arc are poorly constrained by our data, as P_n was not observed on any ocean-bottom instruments. Critical distances of P_mP reflections, however, suggest that velocities increase to about 8.0 km/s over a relatively short vertical distance (<3 km). Along-arc wide-angle reflection and refraction data recorded on Aleutian islands indicate average subcrustal velocities of 7.7 km/s (Fliedner

¹GSA Data Repository item 9905, seismic data and travelt ime fits, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

and Klemperer, 1998). The position of the subducting slab is well constrained by wide-angle reflections on ocean-bottom instruments as far north as model km 175, where the plate boundary is at about 20 km depth. At greater depths, dipping reflections that presumably come from near the top of the slab were observed at 13–17 s two-way traveltimes on the coincident MCS profile (inset, Fig. 1; Bangs et al., 1995); after migration using our velocity profile, these reflections form a dipping zone at 40–50 km depth. Plotting of earthquake hypocenters confirms that these reflections are located appropriately to be the top of the slab. It is interesting that these reflections imply that the slab is ~60 km, not 100 km, beneath the currently active arc, a depth similar to that recently obtained in the Cascadia arc (Parsons et al., 1998). The thick crust in the backarc suggests that the locus of magmatism has migrated south with time, perhaps because of slab rollback (Garfunkel et al., 1986; Hamilton, 1988).

DISCUSSION

Important constraints on continental growth via accretion of intraoceanic arcs can be placed by comparing arc properties to those of mature continental crust. An important question is which characteristics of mature continental crust are generated in arcs and which are acquired during later events. Our results provide an opportunity to compare three large-scale properties—thickness, bulk composition, and internal structure—between Aleutian island-arc crust and mature continental crust.

Our results suggest that the thickness of crust produced in an island arc is sufficient to form continental crust, but that the bulk composition and internal structure are dissimilar to mature continental crust. The 25–30-km-thick crust forms a buoyant block, the likely fate of which is to accrete to a continental margin rather than to subduct. However, the velocity structure, and hence the composition, of the Aleutian crust is rather different from that of continental crust. These differences are demonstrated by a comparison of velocities in the Aleutian arc to those of (1) average continental crust (Christensen and Mooney, 1995) and (2) the accreted terranes of British Columbia (Morozov et al., 1998) (Fig. 2). Both the average continental crust and the accreted terranes have a substantially lower proportion of mafic material in the lower crust than the Aleutian crust has, and both have a distinct upper crustal layer with velocities of 6.1–6.4 km/s, which is lacking in the Aleutian crust.

We can place bounds on the major-element composition of the Aleutian island arc by using the seismic constraints imposed by our model, combined with knowledge of Aleutian lava chemistry (Fournelle et al., 1994) and fractionation models (Kay and Kay, 1985). We calculated a suite of compositional models using a range of plausible compositions for the upper, middle, and

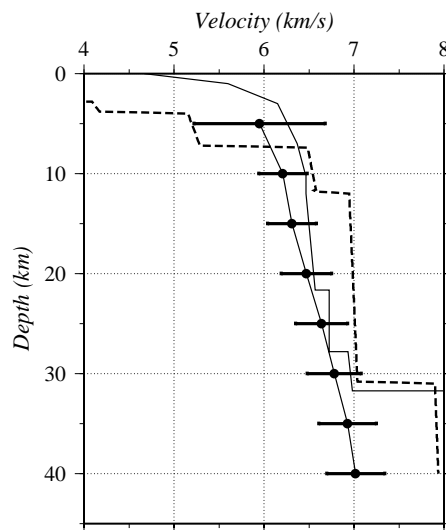


Figure 2. Velocity-depth profile from Aleutian island arc (dashed line), from British Columbia accreted terranes (solid line; Morozov et al., 1998), and for globally averaged continental crust (solid line connecting circles with error bars; Christensen and Mooney, 1995).

lower crust. Candidate rock types were determined from observed lava chemistry in the upper crust (Fournelle et al., 1994) and seismic velocities in the middle and lower crust, and chemical compositions were taken from the compilation of (Fournelle et al., 1994) and the fractionation models of Kay and Kay (1985). Combining chemical compositions in the proportions dictated by the thickness of seismic layers yielded the results in Table 1. Our preferred model has a mixture of basalt and basaltic andesite in the upper crust, MORB in the middle crust, and tholeiitic residuum (47% plagioclase, 33% clinopyroxene, and 20% olivine; Kay and Kay, 1985) in the lower crust. The resulting chemical composition is significantly more mafic than bulk continental crust (Rudnick, 1995).

The Aleutian island arc lacks any seismic evidence for silicic compositions in the middle crust, in contrast to a recent study of the Izu-Ogasawara arc that found a 5-km-thick unit with a velocity of 6.0–6.3 km/s, which Suyehiro et al. (1996) interpreted as granitic. The resulting discrepancy in seismically inferred bulk crustal composition implies that (1) the middle crust of the Izu-Ogasawara arc is anomalously hot or fractured, yielding lower velocities; (2) the low-velocity (4.3–5.0 km/s) upper crust of the Aleutian arc consists predominantly of silicic lavas; or (3) magmatic processes may be different in the two arc systems. We consider the first two possibilities unlikely. However, additional, well-constrained seismic studies of intraoceanic arcs are needed to understand the potential variability in magmatic processes and crustal composition.

Another defining geophysical characteristic of continental crust, the pervasive middle and lower

TABLE 1. ESTIMATES OF BULK CRUSTAL COMPOSITION

	Aleutian island arc*	Average continental crust†
SiO ₂	49.5 ± 0.8	59.1
TiO ₂	0.6 ± 0.2	0.7
Al ₂ O ₃	16.2 ± 0.7	15.8
FeO	8.1 ± 0.4	6.6
MnO	0.2 ± 0.1	0.1
MgO	10.6 ± 1.3	4.4
CaO	13.0 ± 0.8	6.4
Na ₂ O	13.0 ± 0.8	3.2
K ₂ O	0.5 ± 0.2	1.9

*Estimate based on 6 km of basalt + basaltic andesite in upper crust (Fournelle et al., 1994), 5 km of MORB in middle crust (McKenzie and Bickle, 1988, 1280 °C), and 19 km of tholeiitic residuum in lower crust (Kay and Kay, 1985). Error bars represent variation in chemistry using various alternative models of composition (e.g., dacite in the upper crust; calc-alkalic residuum in the lower crust).

†From Rudnick (1995).

crustal reflectivity (e.g., Mooney and Brocher, 1987), is conspicuously lacking in the Aleutian arc. MCS profiles acquired across and along the arc during our experiment (Bangs et al., 1995; McGeary and Aleutian Working Group, 1996) show little intracrustal reflectivity, despite the recording of deep reflections from the slab (Fig. 1). This result indicates that, like the silicic upper crust, pervasive seismic reflectivity is not native to arcs and therefore must be acquired during later tectonic and magmatic events.

These differences in internal structure and bulk composition indicate that, if island arcs serve as building blocks of continental crust, their properties are significantly altered during or after accretion to a continental margin. Two processes must occur in order to transform Aleutian island-arc crust into crust that resembles mature continental crust: a substantial upper crust of silicic composition must be created, and much of the mafic lower crust must be removed. These processes are likely accomplished by a combination of intracrustal melting and delamination of a mafic and/or ultramafic lower crust. Welding of oceanic arc terranes to a continent may result in eclogite formation that would stimulate delamination (e.g., Kay and Kay, 1988; Nelson, 1991). In addition, subduction outboard of a newly accreted terrane may be established, forming a continental arc. Magmas erupting through the thickened crust of the accreted continental margin will be likely to fractionate and form silicic plutons in the upper crust. Intracrustal melting and fractionation are necessary components of the model: delamination of arc lower crust alone is insufficient to drive SiO₂ and MgO compositions from island-arc to bulk-continental values (Table 1). A combination of delamination and partial melting of the lower crust was also proposed by Pearce et al. (1990) based on chemical modeling of exposed island arc terranes. Segregation of cumulate olivine beneath

the seismic Moho during intracrustal fractionation may also help push bulk crustal composition from basaltic toward andesitic.

Our results show that the volume of crust along the arc, and thus the implied magma production rate, exceeds that estimated by previous workers by about a factor of two, which may have important implications for models of continental growth (e.g., Reymer and Schubert, 1984). The volume of material in the arc beneath line A1 is about 5500 km³/km; subtracting a 6-km-thick preexisting oceanic crustal layer yields 4100 km³/km of arc magmatism. If this crust was produced since 75 Ma, the magma production rate is 55 km³/km per 1 m.y., in contrast to the rate of 23–33 km³/km per 1 m.y. inferred by Reymer and Schubert (1984). If we use 55 Ma as the formation age of the Aleutian arc (Scholl et al., 1987), the rate becomes 82 km³/km per 1 m.y. A similar discrepancy appears for the Izu-Ogasawara arc: the volume of arc magmatism on the transect of Suyehiro et al. (1996) is about 3100 km³/km, which yields a magma production rate of 66 km³/km per 1 m.y., given an age of 47 Ma for that arc. Thus recent results suggest island-arc magma production rates of 60 ± 10 km³/km per 1 m.y., in contrast to the 20–40 km³/km per 1 m.y. estimated by Reymer and Schubert (1984). Using their estimate of 37 000 km of globally active arc length, we get a magma production rate of 2.2 km³/yr, exactly twice that of Reymer and Schubert (1984). If the seismic results from the Aleutians and Izu-Ogasawara arcs are representative of island arcs elsewhere, Phanerozoic magma production rates in arcs are substantially higher than previously thought. In order to fully assess whether these higher productivity rates imply a proportionally greater contribution of arc magmatism to Phanerozoic continental crustal growth, we need (1) improved estimates of productivity in other arcs and (2) quantitative estimates of the amount of arc lower crust that delaminates or is otherwise recycled back into the mantle.

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