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<td>Publisher</td>
<td>American Geophysical Union</td>
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Constraints on the composition of the Aleutian arc lower crust from $V_p/V_S$

Donna J. Shillington,1 Harm J. A. Van Avendonk,2 Mark D. Behn,3 Peter B. Kelemen,1 and Oliver Jagoutz4

Received 10 December 2012; revised 15 March 2013; accepted 15 March 2013; published 7 June 2013.

[1] Determining the bulk composition of island arc lower crust is essential for distinguishing between competing models for arc magmatism and assessing the stability of arc lower crust. We present new constraints on the composition of high P-wave velocity ($V_p = 7.3$–7.6 km/s) lower crust of the Aleutian arc from best-fitting average lower crustal $V_p/V_S$ ratio using sparse converted S-waves from an along-arc refraction profile. We find a low $V_p/V_S$ of ~1.7–1.75. Using petrologic modeling, we show that no single composition is likely to explain the combination of high $V_p$ and low $V_p/V_S$. Our preferred explanation is a combination of clinopyroxenite (~50–70%) and alpha-quartz bearing gabbros (~30–50%). This is consistent with Aleutian xenoliths and lower crustal rocks in obducted arcs, and implies that ~30–40% of the full Aleutian crust comprises ultramafic cumulates. These results also suggest that small amounts of quartz can exert a strong influence on $V_p/V_S$ in arc crust. Citation: Shillington, D. J., H. J. A. Van Avendonk, M. D. Behn, P. B. Kelemen, and O. Jagoutz (2013), Constraints on the composition of the Aleutian lower crust from $V_p/V_S$, Geophys. Res. Lett., 40, 2579–2584, doi:10.1002/grl.50375.

1. Introduction

[2] Competing models for arc magmatism make different predictions for the thickness and composition of arc lower crust [e.g., DeBari and Sleep, 1991]. Information on the composition of arc lower crust is also needed to estimate its long-term stability [Jull and Kelemen, 2001; Behn and Kelemen, 2006]. To reconcile the average “andesitic” composition of continental crust with primitive island arc compositions, many models call for foundering of dense mafic-ultramafic cumulates into the underlying mantle [e.g., Arndt and Goldstein, 1989; Kay and Kay, 1993].

[3] However, constraining the composition of the island arc lower crust and distinguishing high-velocity lower crust from upper mantle rocks is difficult because (1) lower crustal arc sections are poorly represented in obducted sections [Kelemen et al., 2003a and references therein]; (2) the primary constraints on the lower crust and upper mantle in many active arcs are xenoliths and P-wave velocities ($V_p$). It is unclear how representative the former may be, and the latter cannot uniquely distinguish between the effects of composition, temperature and melt. For example, $V_p$ of 7.6 km/s beneath the Izu-Bonin-Marianas arc are interpreted to represent hot mantle, possibly with melt [Suyehiro et al., 1996] or ultramafic cumulates [Kodaira et al., 2007]. Even in the absence of elevated temperatures and/or melt, $V_p$ cannot be used to differentiate between different possible lower crustal compositions [e.g., between garnet bearing and plagioclase-free compositions, Behn and Kelemen, 2003; Münntener and Ulmer, 2006] and/or serpentinitized peridotite [e.g., Lizarralde et al., 2002].

[4] Ambiguity in constraining the composition of the deep parts of island arcs with seismic velocities can be reduced by incorporating information on S-wave velocity ($V_S$) and $V_p/V_S$ ratios [e.g., Christensen, 1996]. Here, we combine an analysis of sparse S-wave data from the central Aleutian arc and petrologic modeling to better constrain the composition of the lower crust.

1.1. Existing Constraints on Compositions in the Central Aleutian Arc

[5] Aleutian volcanic rocks exhibit a spectrum of compositions (high-Al basalts, high-Mg basalts, and andesites) and fractionation trends (calc-alkaline and tholeiitic); this compositional diversity has been attributed to variations in fractionation depth, state of stress in the overriding plate, differences in parental magma compositions, and water content [Kay et al., 1982; Myers, 1988; Singer and Myers, 1990; Miller et al., 1992; Sisson and Grove, 1993a; Kelemen et al., 2003b; Zimmer et al., 2010]. These models make different predictions for lower crustal composition. For example, one explanation for the abundance of high-Al basalts is the crystallization of a thick sequence of pyroxenite at depth (possibly due to the presence of water), which would enrich the remaining liquid in Al [Sisson and Grove, 1993a]. The mineral assemblages of lower crustal rocks may also be modified following crystallization by metamorphism, particularly the formation of garnet [Behn and Kelemen, 2006]. The only direct information on the Aleutian lower crust comes from limited xenoliths, many of which are (olivine-) clinopyroxenites [Conrad et al., 1983; DeBari et al., 1987; Yogodzinski and Kelemen, 2007], but it is not clear how representative these are.

[6] Existing active-source seismic data from the Central Aleutians acquired in 1994 with the R/V Maurice Ewing and onshore/offshore seismometers (Figure 1) indicate relatively high $V_p$ in the lower crust of the Aleutian arc [Holbrook et al., 1999; Lizarralde et al., 2002; Shillington et al., 2004; Van Avendonk et al., 2004]. For the lower crust of the oceanic island arc, these range from ~7.0–7.1 km/s.
directly beneath the active arc [Holbrook et al., 1999] to 7.3–7.6 km/s slightly trenchward [Shillington et al., 2004]. There is a sharp step in velocity at the top of the lower crust (~0.4 km/s), and along-arc variations in lower crustal velocity appear to correlate to variations in lava composition [Shillington et al., 2004]. These characteristics were attributed to mafic/ultramafic cumulates and/or garnet granulites in the lower crust [Shillington et al., 2004], but $V_p$ alone cannot distinguish between different possible lower crustal compositions and other explanations, such as partial melt in the subarc mantle or serpentinized mantle in the forearc mantle wedge.

1.2. Analysis of S-wave Arrivals

[7] To constrain the $V_p/V_S$ ratio of the deep Aleutian arc crust, we performed a very simple analysis of sparse converted S-wave arrival times from the arc-parallel wide-angle seismic profile acquired in 1994. Seismometers on the Aleutian Islands recorded shots from the 8000 m$^3$ airgun array of the R/V Maurice Ewing, which steamed south of the islands (Figure 1). Thus, the majority of $P$- and $S$-wave ray paths in this experiment sampled the arc crust trenchward of the active arc, but were still within the arc platform [Shillington et al., 2004; Van Avendonk et al., 2004].

[8] We focus our analysis on arrivals from four stations where converted $S$-wave reflections and refractions were observed at large enough shot-receiver offsets to sample much of the crust (Figure 1). Arrivals occur over source-receiver offsets of 20–180 km and have apparent velocities from ~3 to 4.2 km/s (Figure 2). Consistent with the observation of distinct $P$-wave reflections and refractions from three laterally continuous layers, we identify three crustal $S$-wave refractions with distinct apparent velocities; intracrustal and Moho $S$-wave reflections are also observed (Figure 2 and auxiliary material). Upper crustal arrivals have comparatively 3-D paths due to the experiment geometry, but the longer ray paths of lower crustal refractions and Moho reflections approximately fall in the 2-D plane along the arc platform (Figure 1). Our analysis included 2306 picks; they have large uncertainties (~150–500 ms) because they occur in the coda of the $P$-wave arrivals. Raytracing tests suggest that $P$-to-$S$ conversions occurred at the seafloor or at the top of basement beneath a thin veneer of sediments.

[S] $S$-wave arrivals were previously identified in this data set by Fliedner and Klemperer [1999], who used travel times in independent 3-D $P$- and $S$-wave tomographic inversions. We argue that the paucity of $S$-wave observations and large uncertainties in travel time picks favor an alternate, simpler analysis approach. We searched for the best-fitting constant $V_p/V_S$ ratio for each layer. An $S$-wave model was calculated from the $P$-wave model for each of a range of $V_p/V_S$ ratios. We traced rays through each model in 3-D to produce predicted arrivals times for reflections and refractions, which were used to calculate a RMS misfit. Starting with the upper crust and working down, we found the best-fitting constant $V_p/V_S$ ratio for each layer. A fixed delay of 1.8 s was used to account for structure beneath the stations; a similar approach was used for the $P$-wave modeling [Van Avendonk et al., 2004].

1.3. Results of S-wave Modeling

[10] This approach yielded ranges of best-fitting constant $V_p/V_S$ for the upper, middle and lower crust along the central Aleutian island arc. Here we focus on results for the lower crust. The RMS misfit curve for $S$-wave refractions within the lower crust and refractions off the base of the lower crust (i.e., the Moho) shows a clear minimum at a $V_p/V_S$ of 1.70 (Figure 3). Given the large uncertainties associated with travel time picks of these sparse data and the simple approach taken here, models with $V_p/V_S$ between ~1.65

Figure 1. Map with 1994 Aleutian experiment. Bold orange line shows shotline used in this study. Instruments shown with white circles; instruments whose data are used here shown with orange circles and text. Red triangles indicate volcanoes from the Smithsonian Global Volcanism Program. Plate boundary and convergence directions and rates with respect to North American shown with yellow dotted lines, arrows and text [DeMets et al., 2010].

Figure 2. Data from Nikolski2 (location in Figure 1). (a) $P$-wave arrivals in section reduced at 7 km/s. (b) Converted $S$-wave arrivals in same data reduced at 4 km/s. Reflections from upper (blue), middle (green), lower crust (red), and upper mantle (turquoise). Reflections from base of upper (orange), middle (yellow), and lower crust (purple).
and 1.75 are considered acceptable. However, the apparent velocities of the refractions, alone, indicate a higher $V_p/V_S$ ($\sim 1.75$). Additionally, the average lower crustal $V_p/V_S$ based on regional earthquakes indicates a $V_p/V_S$ of $\sim 1.74–1.77$ [Abers, 1994], and higher lower crustal $V_p/V_S$ are implied in the lower crust directly beneath the active arc by receiver functions at stations along the arc (H. A. Janiszewski et al., 2013, submitted). Thus, we favor the upper end of our acceptable range (1.7–1.75).

1.4. Interpretation of $V_p/V_S$

[11] The new $V_p/V_S$ results presented here combined with the $V_P$ model along the same profile [Shillington et al., 2004; Van Avendonk et al., 2004] provide unique new constraints on island arc lower crust. Below we discuss different possible explanations for our observations.

[12] Although the range of permissible average $V_p/V_S$ ratios from our study is large, it immediately excludes many possible explanations for lower $V_p/V_S$ in the lower crust and/or upper mantle. If $P$-wave velocities of 7.3–7.6 km/s were caused by serpentinization of the mantle wedge approaching the forearc, we would expect relatively high $V_p/V_S$ [e.g., Christensen, 2004, Figure 4]. Likewise, high temperatures and the presence of melt would also increase $V_p/V_S$ [e.g., Faul and Jackson, 2005]. Anisotropy can also influence the estimation of $V_p/V_S$ [Hacker and Abers, 2012]. However, for the ray paths in this study and possible mineral assemblages in the lower crust, we infer that anisotropy is unlikely to completely account for the observed low $V_p/V_S$.

[13] In general, the dominant compositional control on $V_p/V_S$ variations in the crust is silica content; higher silica rocks are generally associated with lower $V_p/V_S$ [Christensen, 1996, Figure 4]. However, in mafic and ultramafic rocks with low SiO$_2$, other minerals begin to play a role in controlling the velocity characteristics. There are several possible constituent minerals that could be present in the Aleutian lower crust that would result in a relatively low $V_p/V_S$ ($\lesssim 1.75$).

[14] Pyroxenite can have $V_p/V_S$ ranging from $\sim 1.68$ to 1.85 (Figure 4), depending on the composition of the pyroxenite (orthopyroxene has a lower $V_p/V_S$ than clinopyroxene) [Behn and Kelemen, 2006]. Many xenoliths from the Aleutians are (olivine-) clinopyroxenites [Conrad et al., 1983; Conrad and Kay, 1984; DeBari et al., 1987; Yogodzinski and Kelemen, 2007]. The estimated $V_p$ of these compositions based on Hacker and Abers [2004] ($7.5–7.8$ km/s) is at the upper end of the $V_p$ range for the lower crust from Shillington et al. [2004] (7.3–7.6 km/s), but the $V_p/V_S$ ratio ($\sim 1.77–1.79$) is higher than the values presented here (Figure 4). Thus, another composition must be present in addition to (or instead of) clinopyroxenite.

[15] Orthopyroxene has a lower $V_p/V_S$ ratio and could be present due to the breakdown of olivine plus plagioclase to form clinopyroxene, orthopyroxene, and spinel [Kushiro and Yoder, 1966]. Alternatively, metasomatism of olivine-rich rocks by silicic fluids can form orthopyroxene at temperatures above serpentine stability but below the soludus (700–1000°C) [Wagner et al., 2008]. Orthopyroxene could fit our observed $V_p$ and $V_p/V_S$ (Figure 4); however, orthopyroxene is not observed in any of the lower crust or upper mantle xenoliths from the Aleutians [Conrad et al., 1983; DeBari et al., 1987]. Therefore, although orthopyroxene may be present, we find it unlikely that it forms in sufficient abundances to explain the observed $V_p/V_S$ ratios.

[16] Another possible contribution to low $V_p/V_S$ is the presence of quartz. Quartz is common in felsic and intermediate arc rocks. Its presence in more mafic rocks could occur due to fluxing of silicic material from the slab [Rossi et al., 2006]. Alternatively, the metamorphic reaction of enstatite and plagioclase forms garnet, clinopyroxene and quartz [Kushiro and Yoder, 1966]. The abundance of quartz in the deep Aleutian crust is unknown; Conrad et al. [1983] reported that a gabbroic xenolith from Adak contains quartz. It is also observed in deep crustal rocks from the obducted Kohistan arc [Yamamoto, 1993; Jagoutz and Schmidt, 2012], but is not observed in lower crustal gabbronorites in the Talkeetna section [Kelemen et al., 2003a; Behn and Kelemen, 2006]. The elastic properties of quartz change dramatically with the transition from alpha to beta quartz; alpha quartz has a much lower $V_p/V_S$ (~1.4) than beta quartz (~1.7) [e.g., Ohno et al., 2006]. The profound effect of the alpha-beta quartz transition is illustrated in Figure 4, which shows $V_p$ and $V_p/V_S$ calculated using Perple_X [Connolly, 2005] for rocks from obducted arc sections in Talkeetna and Kohistan at 0.8 GPa (see auxiliary material). Calculations at 750°C lie within the alpha quartz stability field, and rocks with higher SiO$_2$ trend toward low $V_P$, and low $V_p/V_S$ ratios (Figure 4a). By contrast, velocities calculated at 900°C lie within the beta quartz stability field, and rocks with higher SiO$_2$ trend toward low $V_P$ and high $V_p/V_S$ (Figure 4b). Our rays sample the lower crust trenchward of the active arc line, where colder temperatures are expected, making the stability of alpha quartz more plausible [Shen et al., 1993].

[17] The sensitivity of the expected mineral assemblages arising from different bulk compositions as a function of temperature and pressure was assessed by examining several possible lower crustal compositions derived from obducted arc sections using Perple_X (see auxiliary material). To satisfy the high $V_P$ in the Aleutian lower crust, the presence of quartz, which has low $V_P$, would need to be balanced by other components with higher $V_P$, such as garnet. The pressure-temperature window in which both phases are stable is either nonexistent or very narrow and confined to conditions only present in the lowermost Aleutian crust (Figure S7). Consequently, we conclude that alpha quartz
Figure 4. Seismic velocities of obducted arc rocks from Talkeetna and Kohistan [Kelemen et al., 2003a; Jagoutz et al., 2006]. Phase proportions and velocities were calculated from bulk composition with a version of Perple X modified to include the alpha/beta quartz transition at (a) 750°C and (b) 900°C, which lie in the alpha and beta quartz stability fields, respectively. Squares are ultramafic rocks, and circles are gabbros. We assume gabbros contain 0.5 wt % H₂O and ultramafic rocks are dry. Grey, black, and white triangles are velocities estimated for (olivine-) pyroxenites, dunites, and other compositions (amphibolites and hornblendites) from Aleutian xenoliths, respectively [DeBari et al., 1987] using Hacker and Abers [2004]. Grey bands show range of VP from Shillington et al. [2004] and Vp/Vs from this study. Lines and text indicate VP and Vp/Vs for compositional end-members of olivine (FO-fosterite, FA-fayalite), clinopyroxene (DI-diopside, HED-hedenbergite), and orthopyroxene (EN-enstatite, FS-ferrosillite) from Hacker and Abers [2004]. Serpentinite calculated at 600°C. Almost no compositions fall within observed VP and Vp/Vs ranges for the Aleutian lower crust, suggesting that a mixture of compositions is required.

could contribute to the observed velocity properties of some parts of the crust, but cannot be the sole explanation for the low Vp/Vs ratios over the entire Aleutian lower crust.

[18] Based on the factors discussed above, it does not appear that a single composition can fully explain the VP and Vp/Vs of the Aleutian lower crust, but rather a combination of rock types is required. We favor the interpretation that there is abundant (olivine-) clinopyroxenite in the Aleutian lower crust, consistent with Aleutian xenoliths. These compositions have VP that fall within the upper end of the range of VP observed in the lower crust here, but their estimated Vp/Vs ratios are above the observed range (Figure 4). This requires that other compositions with lower VP and Vp/Vs must also be present to account for the combination of high VP and low Vp/Vs. Specifically, we favor mixtures that include compositions with a small amount (<5 wt %) of alpha quartz, such as rocks with ~50–65 wt % SiO₂ (Figure 4). Mixtures with ~30–50% alpha-quartz bearing gabbro (VP = 7.1 km/s and Vp/Vs = 1.72) and ~50–70% clinopyroxenite (VP = 7.6 km/s and Vp/Vs = 1.775) could account for our observations.

2. Discussion

[19] We analyzed S-wave arrivals to better constrain the composition of the deep part of the Aleutian arc, which includes a thick layer with VP of 7.3–7.6 km/s [Shillington et al., 2004]. We find relatively low Vp/Vs values of ~1.7–1.75 for this layer, which is consistent with abundant clinopyroxenite (as indicated by Aleutian xenoliths) in addition to another composition with lower VP and lower Vp/Vs ratios. We favor gabbro or another evolved composition with small amounts (<5%) of alpha quartz. The pressures and temperatures expected across the arc crustal section from the active arc toward the trench span the alpha-beta quartz boundary, such that even small amounts of quartz could result in large changes in Vp/Vs in the middle and lower crust across island arcs.

[20] We use lower crustal VP and Vp/Vs to estimate that ~50–70% of the lower crust is composed of clinopyroxenite, implying that it forms ~30–40% of the entire Aleutian crustal section. The portion of the Aleutian crust comprising ultramafic cumulates is larger than the proportion of equivalent compositions exposed in obducted arcs, but similar to estimates of their proportions based on geobarometry and mass balances [Kay and Kay, 1985; DeBari and Sleep, 1991; Greene et al., 2006; Jagoutz and Schmidt, 2012]. In contrast to what is interpreted for many other island arcs, we interpret the presence of significant ultramafic cumulates above the seismic Moho, and that our Moho represents the contact between mafic-ultramafic cumulates and mantle. In many arcs, these compositions are inferred to lie beneath the seismic Moho; their high velocities might make them indistinguishable from hot upper mantle, such that the Moho might instead represent a boundary between plagioclase-bearing and ultramafic compositions [Müntener and Ulmer, 2006; Kodaira et al., 2007; Tatsumi et al., 2008].

[21] The presence of abundant clinopyroxenite in the Aleutian lower crust can explain several key characteristics of Aleutian lavas. The crystallization of a thick layer of pyroxenite will result in a higher-Al liquid and could account for high-Al basalts in the Aleutians [Sisson and Grove, 1993a; Müntener et al., 2001]. Likewise, the
depletion of the remaining melt in Fe could explain calc-alkaline fractionation trends [Sisson and Grove, 1993b; Zimmer et al., 2010]. The presence of water in the parental magma suppresses plagioclase, which can enable the crystallization of thick sections of pyroxenite and a more abrupt “plug-in” [Müntener et al., 2001]. Approximately 3–4 wt % H2O is estimated for lavas in the oceanic Aleutian arc from melt inclusions [Zimmer et al., 2010]. Simple petrological modeling suggests that the suppression of plagioclase crystallization due to the presence of water may partially account for the sharp step in Vp at the top of the lower crust in the Aleutians (Figure S8). However, our interpretation of multiple compositions in the lower crust implies that magmas undergo varied crystallization sequences during their ascent, which may also help explain the compositional diversity observed at volcanoes.

3. Conclusions

The analysis of sparse converted S-waves in an along-axis refraction profile in the Aleutian island arc yields low average Vp/Vs ratios for the lower crust. The combination of high Vp and low Vp/Vs is best explained by a combination of abundant clinopyroxenite and another mafic composition containing alpha quartz. This reinterpretation is consistent with Aleutian xenoliths, obducted arc sections, and many petrological models for Aleutian magmas. Better constraints on S-wave velocity in the Aleutians and other arcs can greatly improve our knowledge of arc crustal composition.

Acknowledgments.

We gratefully acknowledge B. Hacker, G. Abers and R. Janiszewski for discussions, J. Connolly for help with Perple X, and M. Fliedner and S. Klemperer for providing information on the Aleutians Experiment. PBK’s contributions supported by the Arthur D. Storke Chair at Columbia University and by NSF grants OCE 0520378, OCE 0728077, and EAR 0727013. The constructive suggestions of two anonymous reviewers and A. Newman greatly improved the manuscript.

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