Constraints on the composition of the Aleutian arc lower crust from \( V_P/V_S \)

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[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 (\( V_P = 7.3 \text{--} 7.6 \text{ km/s} \)) 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 \( \sim 1.7 \text{--} 1.75 \). 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 (\( \sim 50\% \)) and alpha-quartz bearing gabbros (\( \sim 50\% \)). This is consistent with Aleutian xenoliths and lower crustal rocks in obducted arcs, and implies that \( \sim 30\% \text{--} 40\% \) 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 arc 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 \( 7.6 \text{ km/s} \) beneath the Izu-Bonin-Marianas arc are interpreted to represent hot mantle, possibly with melt [Suwada et al., 1996] or ultramafic cumulates [Koda 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; Müntener 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 RV 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 \( \sim 7.0 \text{--} 7.1 \text{ km/s} \)
the Aleutian Islands recorded shots from the 8000 in$^3$ airgun of the active arc, but were still within the arc platform paths in this experiment sampled the arc crust trenchward islands (Figure 1). Thus, the majority of VP $7.3$ velocity appear to correlate to variations in lava composition. There is a sharp step in velocity at the top of the lower crust attributed to ma...
and 1.75 are considered acceptable. However, the apparent velocities of the refrac-
tions, alone, indicate a higher $V_p/V_S$ (~1.75). Additionally, the average lower crush $V_p/V_S$ based 
on regional earthquakes indicates a $V_p/V_S$ of ~1.74–1.77 
[Abers, 1994], and higher lower crush $V_p/V_S$ 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 $V_p/V_S$

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 7.x km/s P-wave velocities in the lower 
crust and/or upper mantle. If P-wave velocities of 
7.3–7.6 km/s were caused by serpentinitization 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 $V_p/V_S$ 
varying 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 $V_p/V_S$ (<1.75).

[14] Pyroxenite can have $V_p/V_S$ ranging from ~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 (~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 silicious fluids can form orthopyroxene at 
temperatures above serpentinite stability but below the 
solidus (~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 interme-
diate arc rocks. Its presence in more mafic rocks could occur 
due to fluxing of silicious 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 gabbrointrites in 
the Talkeetna section [Kelemen et al., 2003a; Behn and 
Kelemen, 2006]. The elastic properties of quartz change dra-
matical 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 crust 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 3. RMS residuals for various lower crustal $V_p/V_S$ 
for $S$-arrivals on instruments shown in Figure 1.
could contribute to the observed velocity properties of some parts of the crust, but cannot be the sole explanation for the low $V_P/V_S$ 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 $V_P$ and $V_P/V_S$ 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 $V_P$ that fall within the upper end of the range of $V_P$ observed in the lower crust here, but their estimated $V_P/V_S$ ratios are above the observed range (Figure 4). This requires that other compositions with lower $V_P$ and $V_P/V_S$ must also be present to account for the combination of high $V_P$ and low $V_P/V_S$. Specifically, we favor mixtures that include compositions with a small amount (<5 wt %) of alpha quartz, such as rocks with ∼50–65 wt % SiO$_2$ (Figure 4). Mixtures with ∼30–50% alpha-quartz bearing gabbro ($V_P=7.1$ km/s and $V_P/V_S=1.72$) and ∼50–70% clinopyroxenite ($V_P=7.6$ km/s and $V_P/V_S=1.775$) 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 $V_P$ of 7.3–7.6 km/s [Shillington et al., 2004]. We find relatively low $V_P/V_S$ 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 $V_P$ and lower $V_P/V_S$ 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 $V_P/V_S$ in the middle and lower crust across island arcs.

[20] We use lower crustal $V_P$ and $V_P/V_S$ 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; DeBarri 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; Zimer 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 major mafic composition containing alpha quartz. This interpretation 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.

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