Seismic evidence for orthopyroxene enrichment in the continental lithosphere

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ABSTRACT

We assess the ability of predicted seismic velocities (Vp, compressional wave; Vs, shear wave; and Vp/Vs) to identify regions in the upper mantle that are enriched in orthopyroxene relative to normal melt-depleted peridotite compositions. Orthopyroxene enrichment has been found in mantle xenoliths from a number of locations, including the Colorado Plateau and the Kaapvaal craton. We find that the Vp/Vs ratio is very sensitive to orthopyroxene concentration, but it is not sensitive to depletion level. We compare these predicted velocities and Vp/Vs ratios to the high Vs, low Vp/Vs anomaly found above the central Chile–Argentina flat slab. Within error, the predicted velocities of some of the orthopyroxene-enriched xenoliths match the observed velocities from the Chile-Argentina upper mantle. Because the anomaly above the central Chile–Argentina flat slab does not conform to known terrane boundaries but does align with the downgoing Juan Fernandez ridge track, we suggest that the orthopyroxene enrichment in this area may be related to flat slab processes, which would have implications for our understanding of lithospheric silica enrichment in the western U.S. and elsewhere.

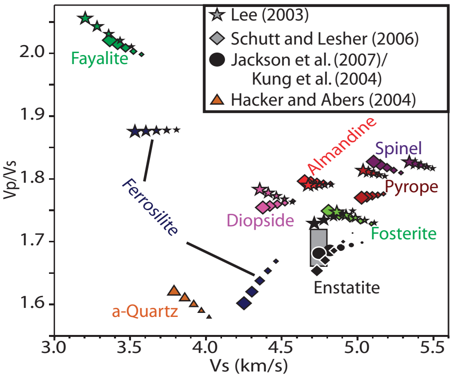

Figure 1. Predicted velocities for peridotite end members at 3 GPa and from 0 to 800 °C (larger symbol = higher temp.) using different sets of elastic constants. Gray rectangle shows range of Vs and Vp/Vs for the anomaly above central Chile–Argentina flat slab.

INTRODUCTION

Advances in the quality and quantity of seismic data made available by increasingly large and densely spaced deployments of broadband seismometers have greatly improved our ability to image P (compressional) and S (shear) wave velocities in the upper mantle. Increasingly, these velocities (together with the Vp/Vs ratio) are being used to try to constrain specific upper mantle properties such as percent melt, temperature, and composition. The sensitivity of Vp, Vs, and Vp/Vs to mantle compositions has been the subject of recent debate (Lee, 2003; Schutt and Lesher, 2006). Lee (2003) calculated predicted seismic velocities for specific xenolith compositions at room (standard, S) temperature and pressure (STP), and found that while Vp and Vs are affected by both temperature and composition, the Vp/Vs ratio is sensitive to composition [specifically Mg# = 100 × Mg/(Mg + Fe)] alone. Schutt and Lesher (2006) calculated predicted velocities for theoretical peridotite compositions with specific levels of melt depletion and found no significant correlation between depletion level and Vp, Vs, or Vp/Vs. Some of the differences between these two studies may be in the different rock compositions analyzed (xenolith versus theoretical), and in the different elastic constants used to calculate seismic velocities (Fig. 1).

Recent reports of unusual velocity structures within some subduction zones may provide an interesting test case for our ability to analyze compositions using Vp, Vs, and Vp/Vs. Each of these studies finds an area in the upper mantle above the downgoing slab characterized by very low Vp/Vs ratios (Eberhart-Phillips et al., 2006; Rossi and Abers, 2006; Wagner et al., 2005; Zheng and Lay, 2006). These ratios range from as low as ~1.6 to as high as 1.74, with typical values generally not exceeding 1.70. Ratios this low are surprising because the mantle above a subducting plate at these depths (<150 km) is generally thought to be hot, wet, and/or partially molten, all properties that tend to increase Vp/Vs, not lower it. Furthermore, these ratios are at times so low that even normal dry peridotite compositions cannot explain them (Eberhart-Phillips et al., 2006; Rossi and Abers, 2006; Wagner et al., 2005). Some have argued that crustal material (α quartz) must be present because no peridotite end member has sufficiently low Vp/Vs ratios to explain these results (Eberhart-Phillips et al., 2006; Rossi and Abers, 2006). Others have noted that orthopyroxene can have very low Vp/Vs ratios that could help explain the observed seismic velocities, especially given the broad range in reported elastic constants for peridotite end members (Wagner et al., 2005) (Fig. 1).

Mantle xenoliths have been found with concentrations of orthopyroxene that are too high to be explained by melt depletion alone (Kelemen et al., 1998). Orthopyroxene-enriched xenoliths have been found in the southern African Kaapvaal craton and in the Colorado Plateau; both of these areas are underlain by ancient depleted lithosphere (older than 3 Ga and 1.6 Ga, respectively). However, the subduction zones exhibiting the low Vp/Vs ratios discussed here are composed of younger accreted terranes, and therefore may not have lithosphere nearly as depleted in terms of Mg# as those sampled by the xenoliths of the Colorado Plateau and Kaapvaal craton. In this paper we look at whether seismic velocities are sensitive enough to the presence of orthopyroxene in order to identify regions of orthopyroxene enrichment, regardless of the depletion level of the mantle material involved. We calculate predicted velocities for the compositions of known orthopyroxene-enriched xenoliths using the elastic constants from both Lee (2003) and Schutt and Lesher (2006) to see whether Mg# (as a proxy for melt depletion level) or orthopyroxene concentration plays a larger role in controlling Vp/Vs. We compare these velocities and Vp/Vs ratios to an improved seismic tomography result, showing the area of low Vp/Vs above the central Chile–Argentina flat slab. We find that while the two sets of elastic constants give very different absolute values of Vp/Vs, they both show that orthopyroxene concentrations control the relative Vp/Vs ratios much more so than Mg#. This suggests that Vp/Vs can be sensitive to composition, but not necessarily melt depletion level. Given the uncertainties both in the predicted velocities and in the tomographic result, it is possible that orthopyroxene enrichment may be responsible for the observed low Vp/Vs anomalies above the central Chile–Argentina flat slab.

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EVIDENCE FOR LOW VP/VS FROM SEISMIC TOMOGRAPHY

We present an updated seismic tomography result for the data set collected as part of the Chile Argentina Geophysical Experiment (CHARGE). The field area for this experiment is of particular interest because the subducting Nazca plate descends normally to a depth of ~100 km, but then flattens, traveling horizontally for several hundred kilometers before resuming its descent into the mantle. The causes of flat slabs are not well understood, but may be related to the subduction of aseismic oceanic ridges, in this case the Juan Fernandez Ridge (van Hunen et al., 2002).

CHARGE consisted of 22 broadband seismometers deployed for ~18 months beginning in late 2000. Details of the deployment can be found in Wagner et al. (2005). For this tomographic inversion, we use the same methodologies described in Wagner et al. (2005, 2006). The improvements in the current models over the previously reported results include an expansion of our data set from 140 events to 881 events, using picks from Anderson et al. (2007), an improved crustal velocity model and Moho depths from Gilbert et al. (2006) and Alvarado et al. (2007), and a new optimized mantle starting velocity model (see the GSA Data Repository[1] for details).

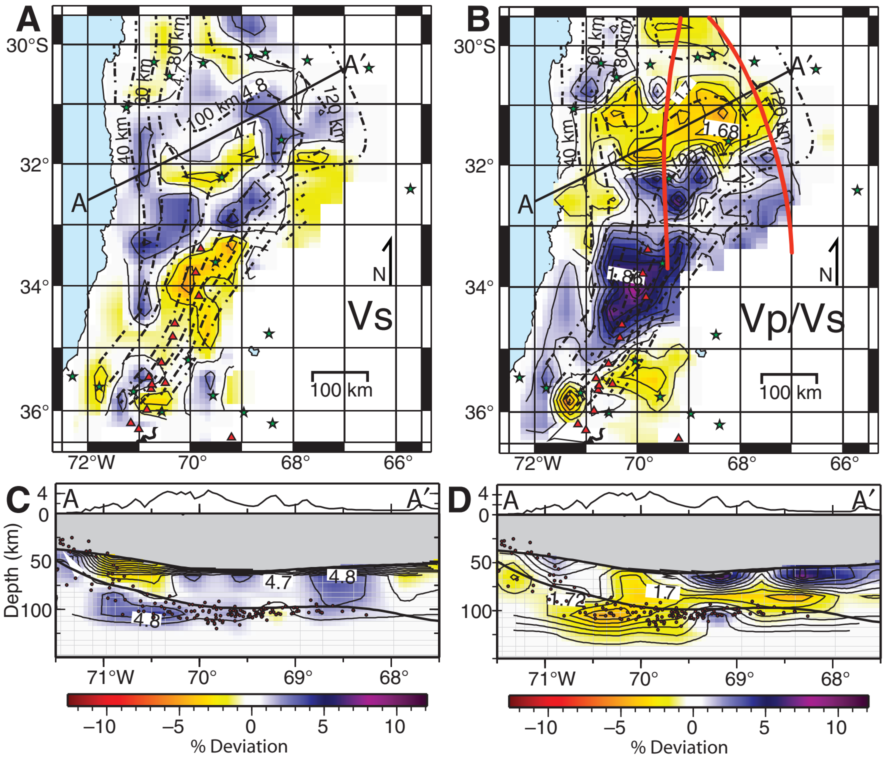

Figure 2. Final tomography results from the CHARGE (Chile Argentina Geophysical Experiment) deployment. A and C show deviations in Vs. B and D show deviations in Vp/Vs. A and B are plotted at 85 km depth. Dash-dot lines show slab contours according to Anderson et al. (2007). Contours are in increments of 0.1 km/s for Vs, and 0.02 for Vp/Vs. Stars show locations of CHARGE stations. Triangles show locations of active volcanoes. Red lines in B show major terrane boundaries. In cross sections C and D, red dots indicate event locations, solid black lines indicate Moho depth (Gilbert et al., 2006) and top of subducted plate (Anderson et al., 2007). Topography is shown above each cross section (note vertical exaggeration).

The results of our inversions are shown in Figure 2. The cross section from A to A′ extends just north of the projected location of the subducted Juan Fernandez Ridge. The anomaly of interest just north of the Juan Fernandez Ridge is characterized by normal to low Vp (7.8–8.2 km/s), high Vs (4.7–4.8 km/s), and very low Vp/Vs ratios (1.65–1.72). This feature can also be seen in cross section as a layer directly above the horizontal portion of the downgoing plate. As discussed in Wagner et al. (2005, 2006), this velocity structure is inconsistent with the presence of typical mantle hydrous phases such as talc, chlorite, or antigorite, despite the fact that previous work on paleo-flat slabs in the western U.S. and beneath the Bolivian Altiplano had suggested that flat slabs serve to hydrate the lithosphere above them (Humphreys et al., 2003; James and Sacks, 1999). Furthermore, the Vp/Vs ratio of this anomaly is much lower than even normal, nonhydrated peridotite compositions at this depth (~1.79; Kennett, 1991). It is, however, consistent with the predicted Vp/Vs ratio for enstatite, depending on which set of elastic constants is used (Fig. 1). In general, the Mg end members of peridotite mineralogies have significantly higher Vs and lower Vp/Vs ratios than their Fe counterparts, which had led us in the past to speculate that the material producing this seismic anomaly must also be extremely depleted (Wagner et al., 2006), though the effect of depletion (Mg#) and orthopyroxene enrichment on seismic velocities had not been quantitatively examined.

VELOCITY CALCULATIONS

In order to calculate our predicted velocities, we use compositions of orthopyroxene-enriched xenoliths from both southern Africa and the Colorado Plateau. The xenoliths range in Mg# from 90.4 to 93.9, and range in orthopyroxene concentration from 10% to 45%. For southern Africa, we use the xenolith compositions from James et al. (2004) listed in their Table 1 under low-T garnet lherzolite, low-Ca harzburgite, and spinel harzburgite for a total of 60 samples. For the Colorado Plateau, we use three of the four compositions documented in Smith et al. (1999). The fourth contained a significant amount of amphibole, which we are not including in our calculations.

We perform our velocity calculations twice, once using the elastic constants and their pressure and temperature derivatives as reported in Schutt and Lesher (2006), and once using the constants reported in Lee (2003). Because Lee (2003) performed calculations only at STP, not all pressure and temperature derivatives are given. Where they are missing for Lee (2003), we use values from Schutt and Lesher (2006). In all cases, calculations are performed assuming 3 GPa pressure and temperatures ranging from 0 °C to 800 °C. Seismic velocities are calculated using the method described in James et al. (2004). This method performs a weighted average of the calculated slownesses for each phase according to the composition of the xenolith in question. As pointed out by James et al. (2004), using such a simple averaging scheme will tend to produce lower velocities than would be obtained with more complicated methods such as Hashin-Shtrickman or Voigt-Reuss-Hill. However, compared to the large differences between the two sets of elastic constants, errors associated with the averaging scheme will be very small (<0.015 km/s; James et al., 2004).

The results of our velocity calculations are shown in Figure 3. In general, Vs decreases with increasing temperature, but the Vp/Vs ratio may increase or decrease depending on the set of constants used and the composition of the xenolith. The shade of the symbols indicates

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[1] GSA Data Repository item 2008238, tomography details, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

either depletion level (Mg#) or orthopyroxene concentration (opx%). We see similar trends for both sets of elastic constants. While there is little to no clear pattern linking Mg# and Vp/Vs, there is a very clear trend between opx% and Vp/Vs, with higher concentrations of orthopyroxene producing lower Vp/Vs ratios.

While the patterns are the same between the two sets of elastic constants, the absolute values are very different. Velocities determined using the constants from Lee (2003) show generally higher Vp/Vs ratios than those determined using the constants from Schutt and Lesher (2006). Looking at the predicted velocities for peridotite end members in Figure 1, it is clear that the main difference is in the values for the Fe and Mg end members of orthopyroxene. This is especially true for ferrosilite. Unfortunately, there have been no recent studies of the elastic constants of ferrosilite (Bass and Wiedner, 1984; Frisillo and Barsch, 1972). Newer research exists for the elastic constants for enstatite (Jackson et al., 2004; Jackson et al., 2007; Kung et al., 2004). These studies indicate that the Vp/Vs ratios for enstatite at 3 GPa and moderate temperatures are closer to those reported by Schutt and Lesher (2006) than those by Lee (2003) (Fig. 1), suggesting that the lower Vp/Vs values may be more accurate.

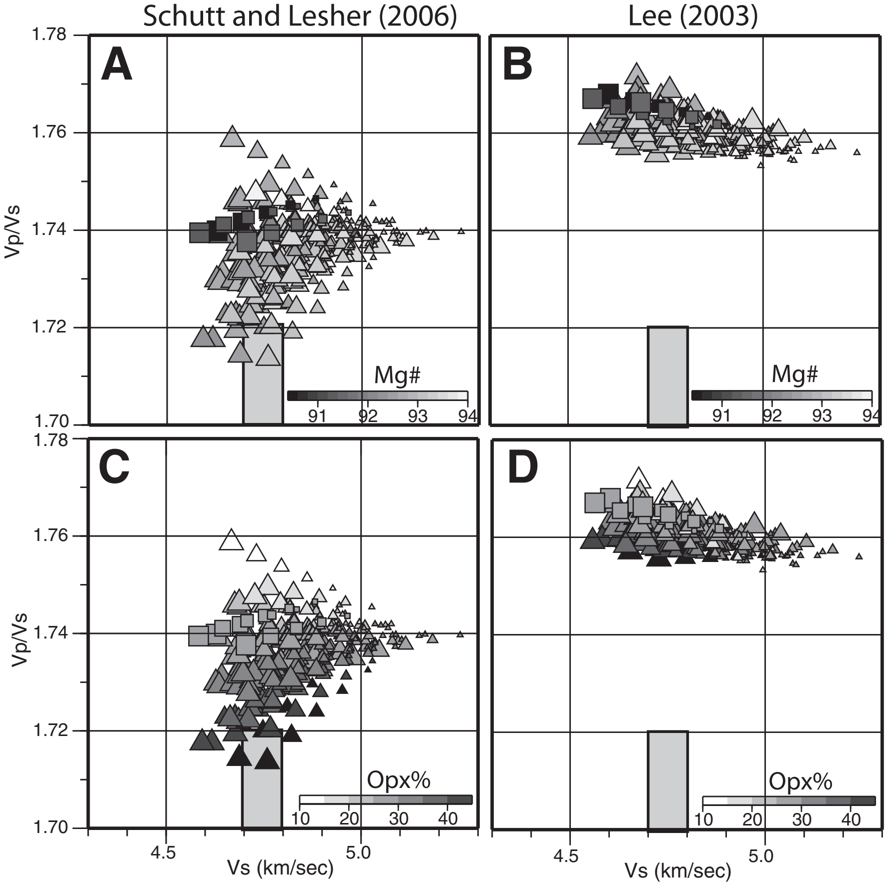

Figure 3. Predicted velocities at 3 GPa and from 0 to 800 °C (larger symbol = higher temperature) for xenolith compositions from Kaapvaal craton (triangles) and Colorado Plateau (squares). A, C: Results using elastic constants in Schutt and Lesher (2006). B, D: Results using elastic constants from Lee (2003). A and B have symbols shaded according to Mg# of xenolith; C and D are shaded according to percent orthopyroxene (opx) (enstatite + Fe) in sample. Gray box shows part of range of Vs and Vp/Vs values for anomaly above central Chile–Argentina flat slab.

DISCUSSION

The relationship, if any, between orthopyroxene enrichment and depletion is important to our understanding of the low Vp/Vs anomaly above the central Chile–Argentina flat slab and elsewhere. The xenoliths used in this study are all from ancient terranes with ages older than 1.6 Ga. In contrast, the low Vp/Vs anomaly above the central Chile–Argentina flat slab crosses at least two terrane boundaries (Fig. 2), with the oldest terrane being at most Grenvillian (1.1 Ga) (Dalla Salda et al., 1992; Ramos et al., 1986). In the past, this was a concern because we believed that depletion level would affect the observed seismic velocities. However, if orthopyroxene enrichment can cause low Vp/Vs ratios irrespective of Mg#, and if the orthopyroxene enrichment process is not necessarily related to melt depletion, then it may be possible that in Chile-Argentina we are looking at an orthopyroxene-enriched mantle layer that traverses several terrane boundaries. This would result in an overprinting of the original lithospheric seismic signature by the later metasomatic event that caused the widespread orthopyroxene enrichment.

The idea that the orthopyroxene enrichment process is separate from major depletion events is supported by work by Bernstein et al. (2007), who noted that the Mg# of xenoliths found in southern Africa is remarkably consistent over a wide range of orthopyroxene concentrations. This Mg# (~92.8) is the predicted Mg# for a mantle peridotite that has been depleted to the point of orthopyroxene extinction, suggesting that the mantle beneath southern Africa had all of its orthopyroxene removed by melt depletion first, and then had the orthopyroxene replaced by some later metasomatic process. If this is true, then the metasomatic process responsible for orthopyroxene enrichment may well be independent of previous depletion events and could occur within less depleted lithospheres as well.

In order to produce such extensive orthopyroxene enrichment, a large quantity of silica must be added to the upper mantle to metasomatize olivine into orthopyroxene. Presumably, the source for this silica would be sediments subducted along with the downgoing plate, which are then transported into the overlying mantle during slab dehydration and subsequent melt-rock or water-rock reactions (Kelemen et al., 1998; Smith et al., 1999). Above the central Chile–Argentina flat slab, the low Vp/Vs anomaly trends parallel to the projected Juan Fernandez Ridge track. While the exact role of the ridge remains uncertain, it is possible that it served as a “sediment snow plow,” especially between 20 and 11 Ma, when the ridge was migrating to the south (Yañez et al., 2001).

It is interesting that silica addition is needed whether the observed low Vp/Vs anomalies are due to orthopyroxene or α quartz, as suggested by Eberhart-Phillips et al. (2006) and Rossi and Abers (2006). Both orthopyroxene and α quartz would serve to significantly lower the Vp/Vs ratio, but α quartz would also significantly lower Vs (Fig. 1). The very high Vs observed above the central Chile–Argentina flat slab limits the amount of α quartz that might be present there (Wagner et al., 2006), but in other subduction zones, the extremely low Vp/Vs ratios observed may require some combination of orthopyroxene enrichment and α quartz addition. Mantle peridotite xenoliths found in Spain show quartz veins with orthopyroxene rims (Arai et al., 2003).

Our study suggests that flat slab subduction may have played a role in the production of orthopyroxene enrichment within the lithospheres of both the Colorado Plateau and the

Kaapvaal craton. This is not a new suggestion for the Colorado Plateau (i.e., Smith et al., 1999), which was underlain by the flat Farallon plate during the Laramide. For the Kaapvaal craton, however, the role of flat slab subduction in orthopyroxene enrichment is much less certain, though slab-derived fluids have been suggested as the metasomatic agents responsible for the observed orthopyroxene metasomatism (i.e., Bell et al., 2005).

CONCLUSIONS

1. We find that, regardless of the set of elastic constants used, calculated seismic velocities for orthopyroxene-enriched xenoliths are more sensitive to the amount of orthopyroxene present than to the level of depletion of the sample (Mg#).
2. The calculated velocities for the most orthopyroxene-enriched xenoliths are consistent with the high Vs, low Vp/Vs anomaly found above the central Chile–Argentina flat slab if newer elastic constants are used.
3. The alignment of the high Vs, low Vp/Vs anomaly in Chile-Argentina with the flat slab and the lack of alignment of this anomaly with known terrane boundaries suggest that the anomaly is related to flat slab subduction processes, but not the original composition of the lithospheres beneath the accreted terranes.
4. If the high Vs, low Vp/Vs anomaly is due to orthopyroxene enrichment, and if it is also related to the flat slab subduction processes, then there may be a direct relationship between flat slab subduction and silica enrichment in the continental lithosphere. This has implications not only for the development of the lithosphere in the western U.S., but also possibly for the formation of silica-enriched cratonic roots.

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