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Shear velocity structure and mineralogy of the transition zone beneath the East Pacific Rise

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ABSTRACT

Models of seismic velocity as a function of depth through the upper mantle provide some of the strongest constraints on the mineralogy and composition of the mantle. Although receiver function studies have provided new information on the depths of upper mantle discontinuities they do not provide as much information on seismic gradients between discontinuities and absolute velocities within the upper mantle. The waveforms and travel times of upper mantle turning waves provide the strongest constraints on vertical variations in upper mantle velocity although in the past they suffered from the lack of dense profiles of data sampling a single part of the upper mantle that would minimize effects of 3D variations in velocity. Here we model three dense profiles of triplicated upper mantle broadband *S* and *SS* waves recorded by USArray, Canadian and NARS-Baja stations located in western North America. Earthquakes along the East Pacific Rise were recorded along profiles within 5° back azimuth windows and with stations at a maximum of 0.5° separation. The distance range covered is from 35° to 60° and thus the waves sample the mantle from the shallow upper mantle to depths near 1000 km. The data were inverted using a conjugate gradient algorithm that utilizes the reflectivity synthetic technique. The results show a much smaller gradient within the transition zone than the PREM model with larger jumps in velocity across the 410 km and 660 km depth discontinuities. These results are consistent with velocities predicted for a pyrolite composition mantle transition zone. Compositional models with lower olivine content, such as piclogite, are not consistent with our seismic model.

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1. Introduction

The mantle transition zone is bound by two significant and ubiquitous global seismic velocity discontinuities near 410 km and 660 km depth, which are believed to result from phase transitions. The 410 km discontinuity is due to the phase transition of olivine to wadsleyite, while the 660 km discontinuity is caused by the endothermic phase change from ringwoodite to perovskite and magnesiowustite (e.g., Bina and Helffrich, 1994). There might also be a small seismic discontinuity near 520 km depth, in light of recent observations (Deuss and Woodhouse, 2001; Shearer, 1990) that is due to the wadsleyite to ringwoodite transition. High pressure mineral physics results have led to efforts to interpret upper mantle seismic models in terms of mineralogy and chemical composition (e.g. Cammarano et al. 2003, 2005a, 2005b; Li and Liebermann, 2007; Anderson and Bass, 1984; Weidner and Ito, 1987; Ita and Stixrude, 1992). For example, the size of the jumps in velocity near 410 km and 660 km depth should place constraints on the amount of olivine in the upper mantle using mineral physics results for the difference in elastic velocities of olivine and wadsleyite. Such comparisons are complicated in that seismic velocity also depends on temperature, water content, as well as other factors. Bass and Anderson (1984) were among the first to note that the "standard" model for the mineralogy of the upper mantle, the pyrolite model (Ringwood, 1975), did a poor job of fitting shear wave velocity in the transition zone. Pyrolite consists of olivine ($\sim$ 55–60% by weight) with lesser amounts of clinopyroxene, orthopyroxene, and garnet. Bass and Anderson (1984) introduced the term piclogite as an alternative mineral composition for the mantle transition zone that they claimed better fit seismic velocities. The piclogite model has much less olivine than pyrolite ($<$ 40%) and more clinopyroxene and garnet (Bass and Anderson, 1984). The Bass and Anderson (1984) study was controversial (Bina and Wood, 1987) as the mineral physics data used involved extensive pressure and temperature extrapolations.

More recently mineral physics studies have confirmed earlier work that showed there is a difficulty matching shear wave seismic models for the upper mantle transition zone to simple mineral model predictions. Li and Liebermann (2007) show that a pyrolite model along a 1600 K adiabat does not match the velocity jump at 410 km nor the transition zone shear velocity gradient when compared to standard seismic reference models such

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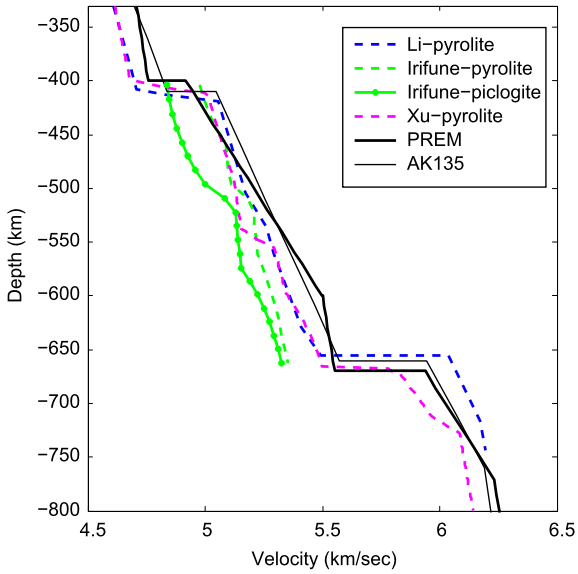

Fig. 1. Comparison of the PREM seismic shear velocity model at 15 sec period (black thick line) and the AK135 seismic model (black thin line) with predictions of shear velocity assuming a pyrolite composition along a 1600 K adiabat. The green dashed line is the prediction from Irifune et al. (2008), the purple dashed line is from Xu et al. (2008) and the blue dashed line is from Li and Liebermann (2007). A prediction of shear velocity assuming a piclogite composition from Irifune and Tsuchiya (2007) is also shown as a solid green line.

as PREM (Dziewonski and Anderson, 1981) or AK135 (Kennett et al., 1995). Li and Liebermann (2007) suggest that further investigation of the water content in the mantle and its effect on elastic properties, as well as consideration of other mantle compositional models over the depth range 400 km to 650 km, are needed. Irifune et al. (2008) show that a pyrolite composition model predicts significantly lower shear wave velocities in the lower part of the transition zone than standard seismic models show, suggesting possible subadiabatic temperatures or the existence of a layer of harzburgite-rich material supplied by subducted slabs stagnant at these depths. Irifune et al. (2008) also show predicted shear velocities for a piclogite composition but the comparison to seismic models is still poor assuming a uniform composition across the entire transition zone. Xu et al. (2008) point out the same discrepancies between shear velocity models and predictions of mineral physics for simple models of chemical composition. In their work they note the difference between a mechanical mixture of basalt and harzburgite versus an equilibrium pyrolite composition but in both cases the jump in velocity at 410 km depth is predicted to be larger than standard seismic models. They also find that shear velocity below 660 km depth is predicted to be lower than seismic models show for an overall pyrolitic composition. Comparisons of the Li and Liebermann (2007), Irifune et al. (2008) and Xu et al. (2008) models to PREM and AK135 are shown in Fig. 1. It is clear that at present there is not good agreement between published reference shear wave velocity models of the transition zone and seismic velocity predictions made using standard mineralogical models. It is not clear what the causes of the discrepancies are, but one possibility is that the seismic models used in these comparisons are not accurate. Consequently, high resolution radial seismic velocity models are required to refine models of the mineralogy of the upper mantle.

Seismic data provide a tremendous amount of information about the Earth's interior. Love and Rayleigh surface waves provide some of the best constraints on the shallow part of the mantle (less than about 200 km depth) but the resolution decreases below 300 km. Surface wave overtones have greater sensitivity at depth than fundamental modes however they have been used at relatively longer periods in past work (Ritsema et al., 2004; Cammarano and Romanowicz, 2007) and thus lack the potential depth resolution of shorter period turning waves. Body wave arrivals are more sensitive to deeper structure. The use of underside reflected precursors of *SS* and *PP* waves (Shearer and Masters, 1992; Shearer, 1993; Shearer and Flanagan, 1999; Deuss et al., 2006) or converted *Ps* or *Sp* waves have been powerful techniques to investigate upper mantle seismic structure (e.g. Ai and Zheng, 2003; Dueker and Sheehan, 1997; Schmandt, 2012). These studies provide strong constraints on topography of upper mantle discontinuities and impedance contrast across the discontinuities. Although it is possible to determine the velocity jump across the discontinuity by using the amplitude versus angle of incidence of reflected or converted waves or combining different type waves (Lawrence and Shearer, 2006), there are usually high uncertainties in the results. Also, these techniques provide no information on velocity gradients between discontinuities.

The travel times and waveforms of triplicated shear waves that turn within the upper mantle have the potential to better constrain *S* velocity structure. For a source at the surface, *S* waves from 15 to 30° distance bottom above 800 km depth while the same triplicated waves can be seen in *SS* waves at double the distance. As an example of wave sampling, Fig. 2a shows a simple shear velocity model based on the published seismic model, TNA (Grand and Helmberger, 1984), as well as a travel time curve (Fig. 2b). Ray paths for an *SS* wave recorded at 47° distance (Fig. 2c) are also shown. Due to discontinuities near 410 km and 660 km depth multiple arrivals are produced at certain distances. At 47° distance, waves turning within the transition zone as well as a wave that turns below 660 km depth arrive at nearly the same time resulting in a complicated waveform. Fig. 2d shows a profile of synthetic *SH* seismograms computed for the model shown in Fig. 2a. Branch AB represents *SS* arrivals that turn above the 410 km discontinuity, at small distances these arrivals turn within the lithosphere. Branch CD represents arrivals turning within the transition zone from 410 to 660 km depth. Finally, branch EF corresponds to waves that have turned below the 660 km discontinuity.

The time separation and amplitude of different branch waves as a function of distance is sensitive to the velocity gradient between the discontinuities as well as to the velocity increase across the respective discontinuities. Note that the CD arrivals are rarely first arrivals but over most distances arrive as secondary arrivals (Fig. 2). The travel time curve reveals that for *SS* wave phases, a complete data profile from 30° to 60° covers all the triplicated arrivals. Thus, with a data profile over this range, we can constrain the velocity structure of the transition zone. The travel times used to construct common reference models like PREM (Dziewonski and Anderson, 1981) or AK135 (Kennett et al., 1995) consist of first arrival *P* and *S* turning waves and thus do not include information from many waves most sensitive to the velocity within the transition zone.

Although shear waves that turn within the upper mantle provide unique sampling of structure, they also have limitations in resolving power that should be kept in mind. The amplitude and timing of turning waves are essentially independent of density. Thus, no information on density structure can be determined, but on the positive side, the insensitivity to density increases the resolving power of velocity relative to techniques that are sensitive to both. Due to relatively low Q in the upper mantle, high signal to noise triplicated shear waves from the upper mantle are limited to relatively long periods from shallow events which limits resolution. The long periods combined with near horizontal paths near the turning points also limit fine scale resolution of structure. In particular, for shear waves with periods of 15 sec and longer, triplicated *S* waves cannot distinguish between a sharp jump in velocity as opposed to a gradient over about 60 km depth (see

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