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Imaging mantle discontinuities using multiply-reflected P-to-S conversions

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ABSTRACT

Improving the reliability and accuracy in the determination of the depth to velocity discontinuities in the Earth's mantle is essential for a better understanding of mantle dynamics, as well as for addressing such fundamental questions as the origin of mantle plumes and fate of subducted slabs. Most existing techniques that utilize receiver function stacking, which is perhaps the most-commonly used method to image mantle discontinuities, suffer from strong trade-offs between the depth and velocity anomalies above the discontinuities. Here we propose and test a procedure that utilizes both the P-to-S converted phase (Pds) and the multiply reflected and converted phase (Ppds) at the discontinuities to simultaneously determine the depth of mantle discontinuities and velocity anomalies in the overlying layer. The procedure includes masking the strong PP arrivals prior to computing receiver functions, computing non-plane wave travel-times for Pds and Ppds for accurate moveout corrections, and utilizing the discrepancies in the apparent discontinuity depths from Pds and Ppds to simultaneously estimate velocity anomalies and discontinuity depths that are independent of velocity anomalies. Application of the procedure to data recorded by stations in seven radius = 1.5° circles along a 780 km N–S profile centered at the Yellowstone hotspot reveals lower-than-normal upper mantle and MTZ velocities beneath Yellowstone, a positive temperature anomaly of 40–190 °C in the vicinity of the 410 km discontinuity (d410), and a lower-than-normal temperature in the vicinity of the 660 km discontinuity (d660). The perceived hotspot is not associated with a localized depression of the d410 or an uplift of the d660, suggesting that the proposed mantle plume does not traverse the MTZ beneath the profile.

1. Introduction

The mantle transition zone (MTZ) is a layer with a global average thickness of about 241–243 km (Flanagan and Shearer, 1998; Gu et al., 1998; Shearer, 2000) bounded by the 410-km and 660-km discontinuities, which are generally believed to be phase transition boundaries in the peridotite mantle (Ringwood, 1975). Temperature, pressure, and water-content dependence of the onset of the phase transitions determines the depths of the discontinuities (Ohtani and Litasov, 2006). Consequently, accurate determination of the depths of the discontinuities and the associated thickness of the MTZ is essential for the understanding of mantle structure and dynamics.

One of the most-commonly used techniques to measure the depths of the discontinuities is stacking of source-normalized radial component seismograms (or receiver functions). The receiver function (RF) technique has been successfully applied to a variety of tectonic settings, such as perceived mantle plumes (Dueker and Sheehan, 1997; Shen et al., 1998; Fee and Dueker, 2004; Cornwell et al., 2011; Schmandt et al., 2012), continental extensional zones (Liu and Gao, 2006; Jasbinsek et al., 2010; Cao and Levander, 2010), subduction zones (Liu et al., 2003; Ai et al., 2005; Ozacar et al., 2008), stable continents (Li et al., 1998; Gao et al., 2002), and on the global scale (Shearer, 1991; Lawrence and Shearer, 2006; Andrews and Deuss, 2008).

A number of previous RF studies used either velocities in a standard Earth model such as the IASP91 (Kennett and Engdahl, 1991) or tomography-derived velocities with large uncertainties for moveout correction and time-to-depth conversion. Due to the intrinsic trade-off between the velocities above the discontinuities and the resulting depths, the resulting apparent discontinuity depths can be significantly different from the true depths. The trade-off is particularly problematic for determining the existence of mantle plumes in the MTZ (e.g., Shen et al., 1998; Foulger et al., 2001; Das-Sharma et al., 2010; Fee and Dueker, 2004; Cao and Levander, 2010; Schmandt et al., 2012), because while the higher-than-normal temperature associated with a mantle plume may lead to a thinned MTZ in an olivine-dominated system (Bina and Helffrich, 1994), the lower-than-normal velocities delay the travel-times of the P-to-S converted phases and result in an apparent thickening of the MTZ. These opposing effects of

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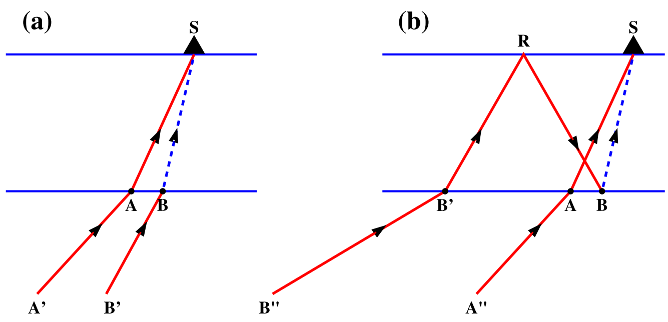

Fig. 1. Schematic diagrams showing the ray path of the direct P-wave (solid line segments) which pierces the discontinuity at point A, and that of the Pds (left plot) and Ppds (right plot). P-to-S conversion takes place at point B. Dashed line segments represent converted S-waves.

mantle plumes on the observed thickness of the MTZ contribute to the controversies regarding the depth extent of mantle plumes.

Here we present an approach to simultaneously estimate the velocity-independent depths ("true depths") of the MTZ discontinuities and the average P- and S-wave velocity anomalies in the overlying layer, by utilizing both P-to-S converted waves from the discontinuities and their multiples. The results can be used to infer anomalies in the temperature and water content in the MTZ (see Ohtani and Litasov, 2006 for a recent review of the effects of temperature and water on MTZ thickness) and be used as first-order constraints for tomographic inversions.

2. Strong presence of the Ppds phase

In this study we refer to the P-to-S converted phase from a discontinuity as Pds. In particular, we use P4s to refer the P-to-S conversion from the d410, and P6s for that from the d660. In addition to Pds, the procedure described below also uses the Ppds phase, which is a P-wave traveling through a discontinuity, being reflected downward by the free surface of the Earth as a P-wave, and then reflected upward by the discontinuity as an S-wave (Fig. 1). Similar to the nomenclature for the direct converted phases, we use Pp4s and Pp6s to represent the Ppds phase associated with the d410 and d660, respectively. While Pds is composed of an S-leg, Ppds is composed of two P-legs and one S-leg (Fig. 1). Although it is not used in the procedure described below due to its weak amplitude, a phase composed of two S-legs and one P-leg is referred to as Psds, which has a negative polarity while Pds and Ppds have a positive polarity (relative to the polarity of the direct P-wave).

To evaluate the observability of the Ppds (and perhaps the Psds) phases associated with the MTZ discontinuities, we requested broadband seismic data recorded by all the stations in a radius = 6° circle centered at (−97°E, 42°N) on the central Great Plains of North America (Fig. 2), from the IRIS (Incorporated Research Institutions for Seismology) DMC (Data Management Center). The data were recorded in the time period between mid-1992 and early 2013. The epicentral distance range of the events is between 40° and 100°, and the cutoff magnitude is calculated using $M_c = 5.2 + (D_e - 30.0)/(180.0 - 30.0) - H_f/700$, where D_e is the epicentral distance in degree, and H_f is the focal depth in km (Liu and Gao, 2010).

The 3-component seismograms are filtered in the frequency band of 0.02–0.2 Hz using a 4-pole, 2-pass Bessel filter, and are converted into radial RFs using the procedure of Ammon (1991). Before the computation of the RFs, we apply a pair of exponential weighting functions with a half width of 30 s and centered at the theoretical arrival time of the PP-phase (t_{pp}) to reduce the amplitude of the PP phase on the vertical, N–S, and E–W components. This step is necessary for reducing the degenerating effect to the resulting RFs by the PP arrivals which have very different ray parameters than the P-waves. The functions are defined as

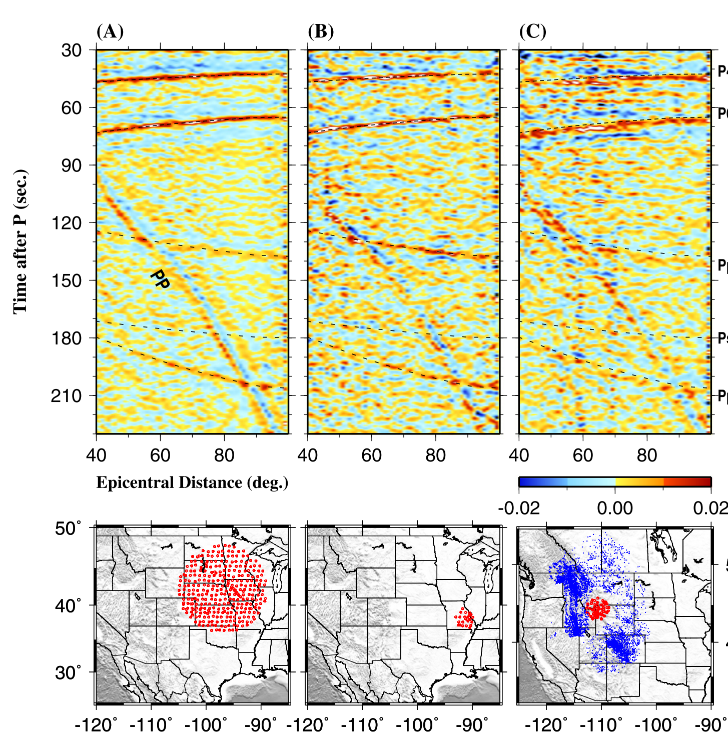

Fig. 2. (Top panels): Radial receiver functions stacked in epicentral distance bins. (A) Results using stations in a radius = 6° circle on the Great Plains of North America; (B) Results using stations from a radius = 1.5° circle in eastern Missouri; (C) Results using stations from a radius = 1.5° circle centered at the Yellowstone hotspot. (Bottom panels): Distribution of seismic stations (circles) used to produce the binned RFs shown in the panel above. Blue dots in the lower-right figure represent Ppds ray-piercing points at 530 km depth.