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Mega ultra low velocity zone and mantle flow

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ABSTRACT

Mantle flow in Earth's interior has been inferred from a variety of geo-disciplines. Two continental-scale, nearly antipodal, large low shear velocity provinces (LLSVPs) at the base of the mantle, thought to be dense and chemically distinct likely play a significant role in mantle dynamics and plume generation, and hence are targeted in a high-resolution seismic study. We analyze broadband SPdKS waveforms using a 2.5D axi-symmetric finite difference wave propagation algorithm PSVaxi. Here we find patches of greatly reduced seismic wave speeds at the core–mantle boundary, i.e., ultra-low velocity zones (ULVZs), within the Pacific LLSVP, including the largest ULVZ detected to date, roughly 250×800 km in lateral dimension and 10–15 km thick, in an apparent hole in the LLSVP. The presence of this ULVZ in the LLSVP hole is well explained by dynamically merging, chemically-distinct piles containing ULVZs at their margins. The consequence of these merging piles may be to initiate anomalously large, infrequent plumes, as well as to provide a means to transfer isotopes to the surface.

1. Introduction

Complex structures at Earth's core–mantle boundary (CMB) relate to and govern important phenomena at mantle-wide scales, such as heat flow from the core and the related cooling of Earth, patterns and vigor of plume upwelling, and long-lived presumed primitive deep mantle reservoirs (Hofmann, 1997; Jellinek and Manga, 2004; McNamara and Zhong, 2005; Thompson and Tackley, 1998). Lowermost mantle heterogeneity at long wavelengths (>1000 km) is dominated by two large low shear velocity provinces (LLSVPs), one beneath the Pacific Ocean and one beneath Africa and the Atlantic Ocean (Becker and Boschi, 2002; Grand, 2002; Gu et al., 2001; Mégnin and Romanowicz, 2000; Ritsema and van Heijst, 2000). LLSVPs possess lower-than-average shear wave velocities compared to the surrounding mantle, with suggestions of elevated density (Ishii and Tromp, 2004; Trampert et al., 2004). The margins between LLSVPs and the surrounding mantle appear seismically sharp (Bréger and Romanowicz, 1998; Ford et al., 2006; He and Wen, 2009; He et al., 2006; Luo et al., 2001; Sun et al., 2009; To et al., 2005). These observations support the proposition that LLSVPs are chemically distinct and slightly negatively or neutrally buoyant thermochemical piles (Deschamps and Tackley, 2009; McNamara and Zhong, 2004, 2005; Nakagawa et al., 2010; Tackley, 2002).

Directly above the CMB in LLSVP regions, thin (5–40 km) and laterally isolated (<100 km) patches of mantle rock exhibit P- and S-wave velocity reductions of 10% and greater (Idehara, 2011; Idehara et al., 2007; Rost et al., 2005; Thorne and Garnero, 2004). S-wave reductions are often reported as approximately 3 times stronger than that of P-wave reductions (e.g., up to 30%), which is well explained by the presence of partial melt (Berryman, 2000; Williams and Garnero, 1996). Called ultra-low velocity zones (ULVZs), this material remains stable at the CMB if it possesses increased density, either from a chemically distinct source (McNamara et al., 2010) and/or the melt phase being denser than the solid (Hernlund and Jellinek, 2010; Nomura et al., 2011).

The surface locations of hot spot volcanism preferentially overlie LLSVP edges (Burke, 2011; Thorne et al., 2004; Torsvik et al., 2006). ULVZs have also been found in the vicinity of LLSVP boundaries (He et al., 2006; Rost et al., 2005), and have thus been suggested to play an important role in plume genesis, hotspot volcanism, and perhaps the formation of large igneous provinces (Garnero and McNamara, 2008; Rost et al., 2005; Torsvik et al., 2006). Geodynamic simulations have demonstrated the dynamic feasibility of ULVZ accumulation at the margins of thermochemical piles (McNamara et al., 2010), with plume initiation preferentially at the peaks of piles. If the sides of chemically distinct piles are relatively steep, a factor that depends on rheology, chemistry, and convective strength, then plumes tend to be in close proximity to pile margins. The present-day structure, geometry, and geographical relationship between seismically imaged ULVZs and LLSVPs, therefore, contain key information

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on deep mantle convective forces that shape them, and hence, past subduction in the circum-Pacific.

The Pacific is an ideal region for studying both LLSVP and ULVZ structure, due to the relative abundance of circum-Pacific recording stations and deep focus earthquakes. In fact, this region has been more extensively investigated for ULVZs than anywhere on Earth using a variety of seismic probes (McNamara et al., 2010; Thorne and Garnero, 2004). However, precise ULVZ physical dimensions and elastic properties are not well constrained in many studies due to inadequate or smeared ray path coverage and/or modeling tradeoffs from use of 1-D waveform modeling tools to resolve 3-D structure (Garnero and Helmberger, 1998).

The confluence of two fundamental advances in seismology makes high resolution ULVZ modeling for this region possible: (1) a wealth of new data has become available as seismic networks expand, such as in N. America over the past 8 years through the addition of the Transportable Array component of EarthScope's USArray (USArray) and additions to the Advanced National Seismic System backbone of seismometers; and (2) increased availability of distributed computing resources enabling the simulation of global seismograms in 2+ dimensions. Here we investigate ULVZ structure beneath the southwest Pacific Ocean using the seismic phase SPdKS and high resolution synthetic seismogram modeling in 2.5D dimensions.

2. Data

We utilize SPdKS, an SKS wave that intersects the CMB at the critical angle for SV-to-P energy conversion, yielding horizontally propagating mantle-side P-diffraction (Pd). Thus SPdKS has short segments of Pd energy that travel on the mantle side of the CMB at the SKS core-entry and exit locations (Fig. 1a). Since the mantle

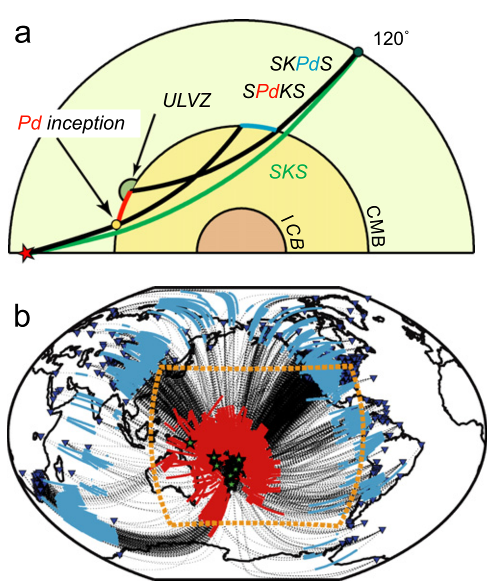

Fig. 1. SPdKS ray path geometry and data collected. (a) Ray path geometry of seismic phases SKS (green), SPdKS (black with Pd section red), and SKPdS (black with Pd section blue). The point where the SKS ray intersects the CMB at the critical angle for P-wave diffraction, generating the Pd portion of SPdKS, is indicated by the yellow circle and the is *Pd inception* point. Many data in this study have Pd inception points before encountering the ULVZ as drawn in green. (b) Collected SPdKS paths are displayed (total of 4221 records). Green stars (earthquakes), blue triangles (receivers), and great-circle ray paths (dashed black lines) are shown with the Pd segments of SPdKS (thick red lines) and SKPdS (thick blue lines) predicted by the PREM (Dziewonski and Anderson, 1981) model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Pd energy sends P energy into the core along entire Pd segments, a single SPdKS is composed of any number of combinations of core versus receiver-side Pd segments (Choy et al., 1980); the nomenclature SPdKS is thus meant to represent all viable possibilities of SPdKS (source-side Pd) and SKPdS (receiver-side Pd) for any source-receiver geometry.

We refer to the point where Pd initiates on the source-side of the ray path for phase SPdKS as the *Pd-inception point*. For average mantle properties, SPdKS first occurs at epicentral distances near 104° (exact distance depends on event source depth), yet the arrival is nearly coincident in time with SKS and does not appear as a distinct arrival until distances near 110°, where SPdKS trails SKS. For an SPdKS wave recorded at 110° the Pd portion of the wavepath along the CMB is approximately 360 km. For an SPdKS wave recorded at 125° the Pd portion of the wavepath along the CMB is approximately 1275 km. Previous efforts have noted that SPdKS waveform effects caused by ULVZs are maximized for records at epicentral distances of roughly 110–112° where SPdKS first emerges and the Pd path lengths are the shortest (Thorne and Garnero, 2004). As the distance increases beyond that, the waveforms behave more similarly to average mantle properties. This is due in part to interfering waves, i.e., SKS and SPdKS at smaller distances, having a more pronounced waveform effect, and in part due to longer Pd paths sampling a progressively larger vertical and lateral scale of D″, and hence, the ULVZ plays a smaller role in perturbing the wavefield. The lateral scale lengths of imaged ULVZs in some locations appear to be on the order of 10's of km (Idehara, 2011; Idehara et al., 2007; Rost et al., 2006). Thus, resolution of small scale ULVZ properties in previous studies has entailed analysis of SPdKS records at epicentral distances less than roughly 115° where the Pd paths are short enough to resolve fine-scale ULVZ structure.

Most seismic probes of ULVZ structure (e.g., ScP, PcP, ScS, and PKP precursors) interact with ULVZs at the CMB reflection or transmission location (Hutko et al., 2009; Rost et al., 2005; Thomas et al., 1999). As a result, studies using these seismic phases provide information about ULVZs in limited geographic locales. SPdKS, however, is sensitive to ULVZ properties over larger lateral spatial scales because of the horizontally propagating Pd segments, but can average or blur structure, especially for longer Pd segments. In this study, we show that SPdKS is strongly sensitive to ULVZ location along the Pd arc. And thus, SPdKS has the ability to constrain ULVZ location (similar to probes like ScP and PcP) but can be used to locate ULVZs over larger spatial extents due to the large lengths of the Pd arcs.

We gathered SKS and SPdKS waveforms from 51 high quality deep earthquakes in the Tonga–Fiji–Kermadec and Java trench regions, recorded at broadband seismic stations around the globe (Fig. 1b), resulting in 4221 total high quality vertically polarized shear wave records between epicentral distances of 90–125°. This corresponded to 2434 SKS records (90–104°) and 1787 SKS+SPdKS waveforms (104–125°). Our criteria for selecting events were as follows: (1) Source depth ≥ 100 km in order to eliminate interference with depth phases, (2) Data must exist for SPdKS waveforms in the distance range $104^\circ \leq \Delta \leq 125^\circ$, (3) The source-time function must be impulsive and simple, and (4) we must be able to unambiguously identify SKS. With respect to criterion (3), we analyzed the source-time function by comparing SKS waveforms at epicentral distances $\leq 110^\circ$ with Hilbert transformed SKKS waveforms. The importance of this step is to ensure that source-time function or receiver effects are not being interpreted as SPdKS waveform behavior. With respect to criterion (4), each individual seismic trace was overlain with a synthetic seismogram computed for the PREM (Dziewonski and Anderson, 1981) model. For each trace the seismic phases SKS and SKKS were identified (and Sdiff for distances where it is noticeable in the SV-wavefield). If the phases SKS and SKKS were not clearly