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Seismic evidence for a chemically distinct thermochemical reservoir in Earth's deep mantle beneath Hawaii

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A B S T R A C T

Nearly antipodal continent-sized zones of reduced seismic shear wave velocities exist at the base of Earth's mantle, one beneath the Pacific Ocean, the other beneath the South Atlantic Ocean and Africa. Geophysicists have attributed the low velocity zones to elevated temperatures associated with large-scale mantle convection processes, specifically, hot mantle upwelling in response to cooler subduction-related downwelling currents. Hypotheses have included superplumes, isochemical heterogeneity, and stable as well as metastable basal thermochemical piles. Here we analyze waveform broadening and travel times of S waves from 11 deep focus earthquakes in the southwest Pacific recorded in North America, resulting in 8500 seismograms studied that sample the deep mantle beneath the Pacific. Waveform broadening is referenced to a mean S-wave shape constructed for each event, to define a relative "misfit". Large misfits are consistent with multipathing that can broaden wave pulses. Misfits of deep mantle sampling S-waves infer that the structure in the northeast part of the low velocity province beneath the Pacific has a sharp side as well as a sloping sharp top to the feature. This sharp boundary morphology is consistent with geodynamic predictions for a stable thermochemical reservoir. The peak of the imaged pile is below Hawaii, supporting the hypothesis of a whole mantle plume beneath the hotspot.

1. Introduction

The present-day chemistry and dynamics of Earth's deep mantle relate to how the mantle as a whole operates, today as well as in the past, including processes relating to the formation and evolution of the planet's core. The behavior of the deep mantle also may influence a number of surface phenomena ranging from driving large-volume intraplate volcanism to regulating the frequency of magnetic reversals. Data that help to constrain our understanding of the deep interior span the geo-disciplines, but seismology provides the most direct means of imaging deep structural features across a range of spatial scales.

Seismic tomography has revealed the presence of two nearly antipodal large low shear velocity provinces (LLSVPs) at the base of the mantle (Masters et al., 2000; Mégnin and Romanowicz, 2000; Grand, 2002; Houser et al., 2008; Ritsema et al., 2011; Lekic et al., 2012). These LLSVPs are located beneath Africa and the Pacific, regions that exhibit numerous surface hotspots and are far removed from deep extensions of current and geologically recent subduction (Fig. 1a). An apparent anti- or non-correlation between bulk and shear modulus in some LLSVP regions (Masters et al., 2000) along with suggestion of increased density (Ishii and Tromp, 1999; Trampert et al., 2004) support the possibility that they may be compositionally-distinct from the background lower mantle.

The strongest horizontal gradients in tomographically derived shear velocity occur at the LLSVP margins (e.g., Thorne et al., 2004; Torsvik et al., 2010; Lekic et al., 2012), which coincide with sharp transitions (50–100 km or less) found in high-resolution seismic studies (Ritsema et al., 1998; Wen, 2001; Luo et al., 2001; Ni et al., 2002; Ford et al., 2006; To et al., 2005; Sun et al., 2007; He and Wen, 2009, 2012) (Fig. 1b, Fig. S1, Supplementary Material). The high-resolution analyses primarily rely upon pulse-broadening of seismic waves that traverse the lowest 100–200 km of the mantle (Fig. S2, see also Table S1, Supplementary Material). This pulse-broadening occurs when seismic energy travels both outside and inside the LLSVP, often resulting in two distinct arrivals.

The vertical extent of LLSVP structure up off the core–mantle boundary (CMB), including sharp edges, has also been inferred by seismic wave travel times in several studies (Ritsema et al., 1998;

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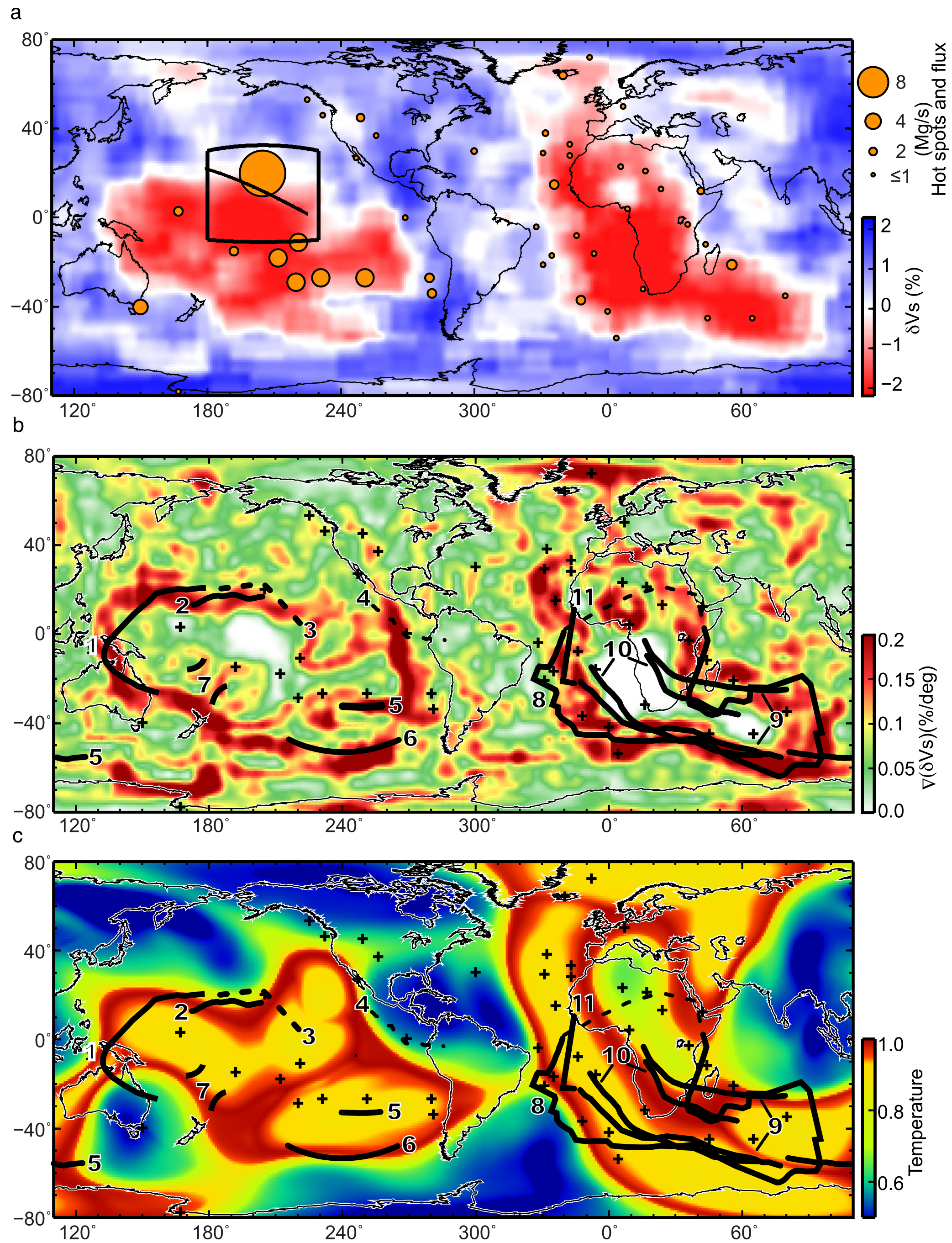

Fig. 1. Geographic correlation between lowermost mantle shear velocity tomography, lateral gradients, and imaged edges. (a) Hotspot locations (orange circles) are plotted on top of a global tomography shear velocity model TXBW (Grand, 2002) at 2750 km depth. Blue and red colors represent higher and lower velocities, respectively. Hotspot size is scaled to the flux of each hotspot (Sleep, 1990). The black box denotes the study region of this paper. The solid black line inside of the box indicates the location of the cross-section in Fig. 6. (b) Lateral shear velocity gradients in model TXBW (red = strongest gradients) are plotted with LLSVP edges (thick black lines, dashed if from travel time inference) found in previous studies (numbers in the figure correspond to Table S1, prominently). Hotspot locations are crosses. Gradients are calculated following a least-square linear curve-fitting algorithm (Thorne et al., 2004). (c) Similar to (b), but displayed are lateral variations of the temperature field calculated from a thermochemical convection model (Garnero and McNamara, 2008). Strongest gradients in (b) and temperatures in (c) are similar – they are near LLSVP margins found in high-resolution studies.

Wen, 2001; He and Wen, 2009, 2012; Lekic et al., 2012). Some of these studies fix the shear velocity reduction within the LLSVP to be a constant value, resulting in a trade-off between velocity reduction and imaged LLSVP height (and shape). Thus, while the geographical distribution of reduced shear velocities in the lowest couple hundred km appears fairly well established (e.g., Becker and Boschi, 2002; Lekic et al., 2012), LLSVP structure up into the lower mantle is less so.

The height and morphology of LLSVP structure depends critically upon the density and viscosity differences between the LLSVP and the surrounding mantle (McNamara and Zhong, 2005; Tackley et al., 2005; Tan et al., 2011). Several possible dynamical frameworks are presented in Fig. 2. Each of the four possibilities in Fig. 2 holds promise in matching the two principle seismic observations of significant shear velocity reductions in the LLSVP and sharp LLSVP sides. However, different geometries