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Implications of lower-mantle structural heterogeneity for existence and nature of whole-mantle plumes

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ABSTRACT

Recent seismological studies demonstrate the presence of strong deep-mantle elastic heterogeneity and anisotropy, consistent with a dynamic environment having chemical anomalies, phase changes, and partially molten material. The implications for deep-mantle plume genesis are discussed in the light of the seismological findings. Nearly antipodal large low–shear velocity provinces (LLSVPs) in the lowermost mantle beneath the Pacific Ocean and Africa are circumscribed by high-velocity regions that tend to underlie upper-mantle downwellings. The LLSVPs have sharp boundaries, low V_S/V_P ratios, and high densities; thus, they appear to be chemically distinct structures. Elevated temperature in LLSVPs may result in partial melting, possibly accounting for the presence of ultra-low-velocity zones detected at the base of some regions of LLSVPs. Patterns in deep-mantle fast shear wave polarization directions within the LLSVP beneath the Pacific are consistent with strong lateral gradients in the flow direction. The thermal boundary layer at the base of the mantle is a likely location for thermal instabilities that form plumes, but geodynamical studies show that the distribution of upwellings is affected when piles of dense chemical heterogeneities are present. The location of lowermost mantle plume upwellings is predicted to be near the boundaries of the large thermochemical complexes comprising LLSVPs. These observations suggest that any large mantle plumes rising from the deep mantle that reach the surface are likely to be preferentially generated in regions of distinct mantle chemistry, with nonuniform spatial distribution. This hypothesis plausibly accounts for some attributes of major hotspot volcanism.

Keywords: core-mantle boundary, D″, plumes, thermochemical piles, hotspots

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INTRODUCTION

The depth of origin of the source of long-lived hotspot volcanism has been of great interest to geological scientists for decades (e.g., Morgan, 1971). This question intersects nearly all Earth science disciplines, and hence continues to attract active debate. The most common interpretation is that thermal plumes rise from an internal mantle thermal boundary layer and sustain hotspot activity. As long as heat is flowing into the base of the mantle from the core—an apparent requirement for long-term maintenance of the geodynamo (e.g., Buffett, 2002)—a thermal boundary layer should be present at the base of the lower mantle. This boundary layer is commonly invoked as the source of deep mantle plumes (see Lay, 2005), consistent with the early notions advanced by Morgan. Certainly, cylindrical plumes commonly initiate from the basal boundary layers in numerical and experimental convection experiments with basal heating or basal injection of fluid (e.g., Davies, 1990; Olson and Kincaid, 1991; Farnetani and Richards, 1994; van Keken, 1997; Farnetani and Samuel, 2005; Lin and van Keken, 2005), carrying heat and any unique isotopic signatures from the boundary layer to the surface. However, demonstrating that such plumes rise ~2900 km from the core-mantle boundary (CMB), traversing the Earth's entire mantle, has proven challenging. Many discussions of this problem invoke very simple notions of the lower-mantle boundary layer, at odds with recent seismic findings. Our goal is to place the question of deep-mantle plume genesis in the context of current seismological and geodynamical ideas about lower-mantle structure and processes. We will avoid the issue of connecting specific hotspot observations to plumes or alternate explanations, as that is addressed in detail elsewhere in this volume (e.g., Sleep, this volume). Our focus is on the implications of seismically defined lower-mantle structures for the occurrence and characteristics of any plumes that do rise from the lowermost mantle.

A number of fields (e.g., seismology, geodynamics, and geochemistry) have presented arguments and some evidence for deep mantle plumes (e.g., Ji and Nataf, 1998; Lin and van Keken, 2005; Montelli et al., 2006; Wen, 2006), but the issue is still under debate, and an increasing number of studies find that some hotspots do not require origins in the lower mantle (e.g., Cserepes and Yuen, 2000; Foulger and Pearson, 2001; Foulger et al., 2001; Courtillot et al., 2003). In this article, we focus primarily on the elastic structure of the deep mantle derived by seismic methods and the dynamics of plume initiation, stability, fixity, and longevity in the presence of the large-scale chemical heterogeneity suggested by the seismic results, including the fact that hotspots are typically only found away from regions of subduction. Over the past several years, a variety of deep-mantle structural characteristics have emerged from high-resolution imaging with broadband seismic data. These structures include chemically distinct provinces beneath the Pacific Ocean and Africa, thin ultra-low-velocity zones (ULVZs) at the CMB, deep-mantle seismic wave anisotropy, and variable occurrence and topography of the D″ seismic velocity discontinuity. This article considers these deep-mantle findings, exploring their implications for the possibility of lowermost mantle plume origination. Key seismological observations are summarized in the next section, followed by a section that considers the chemistry and dynamics of these features. This description provides a framework for considering the implications for any deep mantle plumes that may rise to the surface.

LOWERMOST MANTLE SEISMIC VELOCITY STRUCTURE

It has been known for decades that relatively high seismic velocities in the deep mantle tend to underlie past or present subduction zones, whereas lower-than-average wavespeeds are commonly found beneath the Pacific Ocean, the southern Atlantic Ocean, and Africa (e.g., Dziewonski, 1984; Hager et al., 1985). The distribution of lower-mantle velocities is quite consistent among recent tomographic S-wave velocity (V_S) models, but there is less consistency among P-wave velocity (V_P) models (Fig. 1). The differences between large-scale lower-mantle V_S and V_P heterogeneity have led to the inference that the origin of the velocity perturbations is not solely thermal (e.g., Masters et al., 2000). Unfortunately, until the V_P maps are better resolved (as indicated either by agreement between results from different studies or by demonstration that a particular study has produced the most robust results), it is difficult to confidently separate chemical and thermal effects based on the patterns of heterogeneity at the present time.

It has recently been demonstrated that the expected primary lower-mantle mineral—$(Mg,Fe)SiO_3$, magnesium silicate in perovskite structure (Pv)—should undergo a phase transformation at pressure-temperature conditions within a few hundred kilometers above the CMB (Murakami et al., 2004; Oganov and Ono, 2004; Tsuchiya et al., 2004; Lay et al., 2005). Pv transforms into a post-perovskite structure (pPv) that is predicted to be accompanied by a V_S increase of several percent, but little change in V_P. This difference in response could be one cause of decoupling of variations in V_S and V_P in the lowermost mantle. The V_S/V_P ratio should be highest in high–shear velocity regions because the phase transition will occur at shallower depths in cool regions that have higher seismic velocities to begin with. One challenge in seeking this behavior is uncertainty in the reference level for measuring velocity anomalies; for example, the increase in temperature in the thermal boundary layer above the CMB will tend to lower seismic velocities, with more pronounced effects on S-wave velocity than for P-wave velocities. As seen in Figure 1, most seismic models tend to have means of zero at a given depth, which affects inferences about relative velocity behavior significantly.

The circum-Pacific band of high shear velocities apparent in Figure 1 is plausibly linked to occurrence of pPv in regions with relatively low temperatures below present-day and historic subduction zones. If this link is the case, the large low–shear ve-

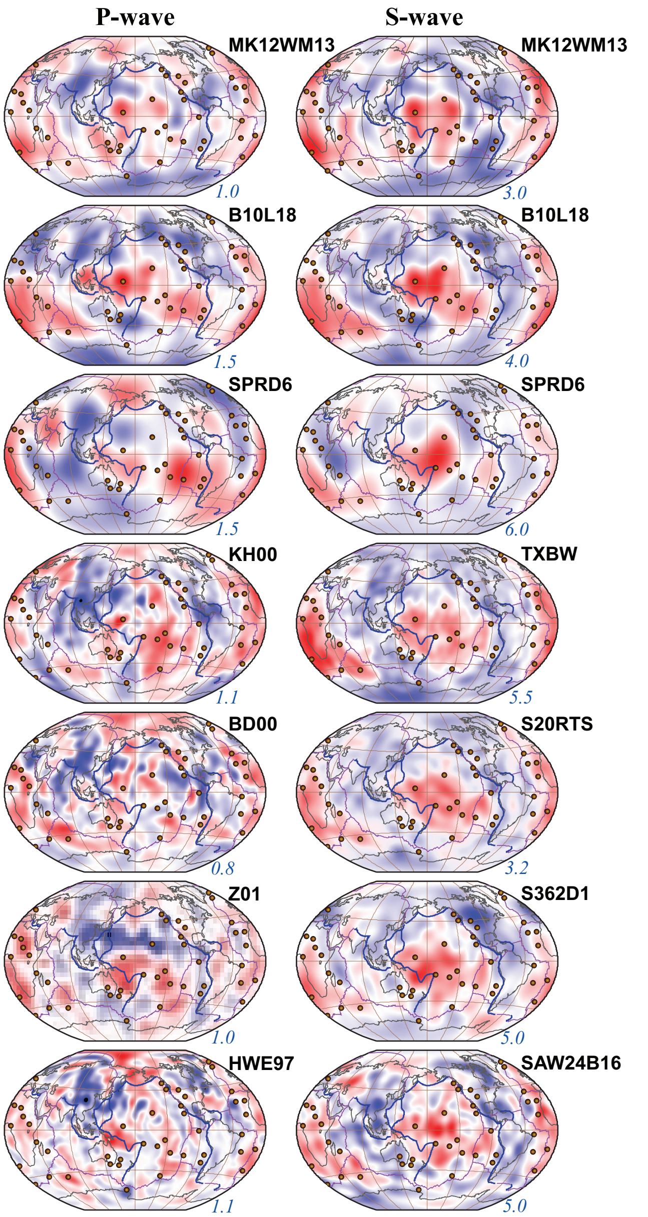

Figure 1. Tomographically derived P-wave (left column) and S-wave (right column) velocity perturbations at the base of the mantle. Red and blue colors indicate lower and higher velocities than global averages, respectively. Color scales are not uniform for the different models; the peak-to-peak value is indicated in the lower right of each map (blue number). Model names are given in the upper right and correspond to the following studies: MK12WM13 (Su and Dziewonski, 1997), B10L18 (Masters et al., 2000), SPRD6 (Ishii and Tromp, 2004), KH00 (Kárason and van der Hilst, 2001), TXBW (Grand, 2002), BD00 (Becker and Boschi, 2002), S20RTS (Ritsema and van Heijst, 2000), Z01 (Zhao, 2001), S362D1 (Gu et al., 2001), HWE97 (van der Hilst et al., 1997), and SAW24B16 (Mégnin and Romanowicz, 2000). More information comparing many of these models is found in Becker and Boschi (2002). Hotspot locations (from Steinberger, 2000) are shown as red-filled circles. Plate boundaries are magenta lines, but convergent boundaries are shown in blue.

locity provinces (LLSVPs) beneath Africa and the Pacific might have no pPv or only a very thin layer of it, and may be relatively warm. The Pv-pPv phase boundary has a large positive Clapeyron slope that would allow large lateral variations of thickness of a layer of pPv within the boundary layer to be caused by large-scale thermal variations. The LLSVPs are basically isolated from locations where subduction has occurred over the past 200 m.y., which is commonly invoked as an indication of control on the deep seismic heterogeneity by large-scale mid-mantle convection coupled to the shallow subduction history. The relatively low shear velocities in LLSVPs can thus be attributed to a combination of relatively high temperature and lack of pPv, but there are indications that there is also a chemical anomaly present in the LLSVPs.

Several free-oscillation studies have found evidence for lateral variation in large-scale lowermost-mantle density distribution (Ishii and Tromp, 1999, 2004; Kuo and Romanowicz, 2002; Trampert et al., 2004). Although debate continues on this topic (Romanowicz, 2001; Masters and Gubbins, 2003), indications are that a density increase is associated with the strongest V_S reductions located in LLSVPs (e.g., Ishii and Tromp, 1999; Trampert et al., 2004). Simultaneous analysis of V_S and V_P behavior further suggests that LLSVPs have bulk sound velocity anomalies (increases) that are anticorrelated with the low–shear velocity anomalies (e.g., Masters et al., 2000). These observations suggest that LLSVPs are chemically distinct from the surrounding mantle. This possibility immediately complicates the interpretation of these regions, because chemical differences can also affect the occurrence of the pPv phase change, and some compositional effects, such as iron enrichment, tend to reduce shear velocity as much or more than high temperature does at high pressures. The presence of iron or aluminum can also affect the phase transition pressure and sharpness (see Lay et al., 2005), although the magnitude of such effects is being debated. Sorting out these tradeoffs requires more detailed structural information than provided by tomography alone.

Portions of LLSVPs have been characterized at relatively short scale lengths (e.g., study regions spanning 500–1000 km laterally) using forward modeling of body wave travel times and waveforms. For example, a significant number of LLSVP margins (Fig. 2) show strong evidence for an abrupt lateral transition over a few hundred kilometers or less between the LLSVP and surrounding mantle. The sharpness of the LLSVP margins supports the notion that there is a chemical contribution because thermal gradients should be more gradual. Additionally, weak reflections from a velocity decrease in the upper portion of the LLSVP in the Pacific may indicate a chemical boundary (Lay et al., 2006) or a phase boundary within chemically distinct LLSVP material (Ohta et al., 2007). Additional internal layering within the LLSVP beneath the Pacific has been inferred from seismic wavefield reflectivity resolved by stacking a large number of seismic data (Lay et al., 2006). In Lay et al. (2006), the northern portion of the LLSVP beneath the Pacific Ocean is found to have a sharp velocity increase overlying a sharp decrease that

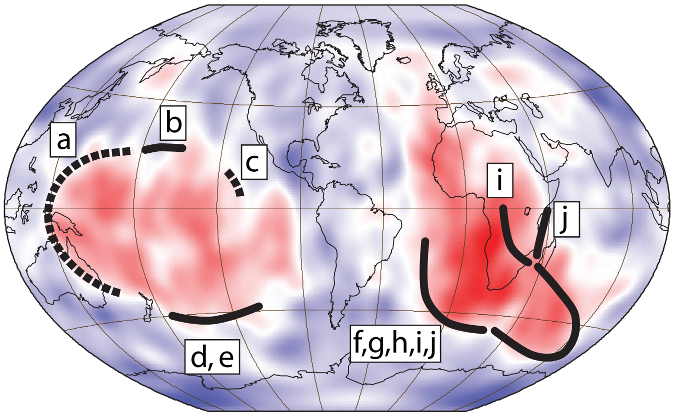

Figure 2. Map showing lowermost-mantle V_S perturbations from model TXBW (Grand, 2002; color scale is the same as in Fig. 1), along with locations where seismic studies have inferred distinct edges to the large low–shear velocity provinces (LLSVPs; thick black lines) using waveform and/or travel time analyses. Lower-cased letters in boxes indicate specific studies for different regions: a (He et al., 2006), b (Luo et al., 2001), c (Bréger and Romanowicz, 1998), d (To et al., 2005), e (Ford et al., 2006), f (Ni and Helmberger, 2001), g (Wen et al., 2001), h (Ni et al., 2002), i (Ni and Helmberger, 2003a,b), j (Wang and Wen, 2004). Solid lines indicate regions with sharp lateral boundaries, and dashed lines indicate regions where the LLSVP edges are only loosely resolved by travel time analysis.

was attributed to forward and reverse transformations of Pv to pPv (as predicted by Hernlund et al., 2005). This region is also underlain by a mild ULVZ (Avants et al., 2006). Lateral depth variations of the mapped perovskite phase boundaries within the LLSVP are consistent with a lateral increase in temperature toward the LLSVP margin in the central Pacific region.

In addition to evidence for sharp boundaries of the two LLSVPs, several forward modeling studies have advocated a chemical origin for isolated seismic heterogeneities at small to intermediate scales (500–1000 km; e.g., Wysession et al., 1994; Bréger and Romanowicz, 1998), as well as at small scales (one to tens of kilometers) that scatter seismic waves and contribute to high-frequency coda energy (e.g., Hedlin and Shearer, 2000; Earle and Shearer, 2001). Some of the small-scale scattering features at the CMB have been attributed to partial melt of deep-mantle material (e.g., Vidale and Hedlin, 1998; Wen and Helmberger, 1998, Rost et al., 2005), owing primarily to magnitude of the requisite velocity reductions and a 3:1 V_S:V_P velocity reduction ratio. It is difficult to attribute large deep-mantle velocity reductions (e.g., >10%) to any expected deep-mantle materials in the absence of some level of melt; in fact, the possibility of partial melt in the deep mantle has been advocated as an explanation for the occurrence of thin ULVZs right above the CMB (Williams and Garnero, 1996; Revenaugh and Meyer, 1997). ULVZs appear to exist preferentially beneath low-V_S regions, including the two LLSVPs (e.g., Garnero et al., 1998; Williams et al., 1998). This preference is hard to quantify because the global distribution of ULVZ structure is not presently well constrained; less than half of the surface area of the CMB has been even qualitatively characterized (Thorne and Garnero, 2004). However, the CMB in some isolated spots has been analyzed in great detail, suggesting partial melt in small domes, small dense zones with a flat top, and even small pockets right beneath the CMB with anomalous properties (Wen and Helmberger, 1998; Helmberger et al., 1998, 2000; Wen, 2000; Rost and Revenaugh, 2001; Rost et al., 2005). These structures all point to complex processes occurring down to small scales, undoubtedly related to high temperatures at the base of the mantle thermal boundary layer.

Lowermost-mantle seismic wave anisotropy may also offer clues to deep-mantle chemistry and dynamics; as suggested by seismic studies (e.g., see Kendall and Silver, 1998; Lay et al., 1998; Kendall, 2000), mineral physics calculations (e.g., Stixrude, 1998; Karki et al., 1999; Mainprice et al., 2000; Wentzcovitch et al., 2004; Hirose, 2006; Hirose et al., 2006), as well as by geodynamics experiments (e.g., McNamara et al., 2001, 2002, 2003). Several seismological studies have mapped geographical changes in the fast propagation direction of deep-mantle shear waves (Russell et al., 1998; Garnero et al., 2004; Wookey et al., 2005; Rokosky et al., 2006). In one case, geometrical patterns in fast propagation directions have been interpreted as being related to lowermost-mantle boundary layer convective currents that may involve flow into a boundary layer upwelling, possibly related to a plume that rises to the Hawaiian hotspot (Russell et al., 1998). Given that there is a first-order correlation between the distribution of surface hotspots and the locations of the LLSVPs (e.g., Thorne et al., 2004; any correlation is less apparent for P-wave velocity heterogeneity) at the base of the mantle (Fig. 1), it is reasonable to seek any evidence for plumes extending through the mantle above these regions.

Direct seismic imaging of any deep mantle plumes is very difficult, primarily owing to the expected small dimension of the plume conduit (e.g., <500 km) compared to the long seismic wave propagation paths (typically >5000 km; see, e.g., Nataf, 2000; Dahlen, 2004). Most tomographic efforts have not directly imaged vertically continuous deep mantle plumes or their relationship to LLSVPs, as the minimum lateral wavelength of resolvability is commonly >1000 km. One notable exception is the study by Montelli et al. (2004), in which several surface hotspots are inferred to be underlain by low V_P values extending down to the CMB (this observation is currently under active debate; see Dahlen and Nolet, (2005); de Hoop and van der Hilst, 2005). The seismological community may eventually converge on models that either support or refute the existence of whole-mantle low-velocity plume conduits. However, deep-mantle seismic plume detection may be almost impossible if plume temperature does not significantly exceed the surrounding mantle (e.g., Farnetani, 1997; Farnetani and Samuel, 2005), giving too small an elastic velocity signature. If the velocity perturbations are, in fact, strong enough, there is some hope to image plume features if wavepath coverage is dense enough (e.g., Tilmann et al., 1998), but at present, this imaging does not appear to have been done convincingly.

Less direct approaches, such as correlation studies of surface hotspot distributions and deep-mantle velocity patterns have been pursued over several decades (e.g., Morgan, 1971; Hager et al., 1985; Thorne et al., 2004), but such analyses do not unequivocally constrain or require the existence of whole-mantle plumes.

LOWER-MANTLE CHEMISTRY AND DYNAMICS

Several conceptual models have been developed in recent years to explain the observed LLSVPs. It proves dynamically difficult to account for the huge low-velocity anomalies beneath Africa and the Pacific in an isochemical mantle, even in models that impose a large-scale pattern of downwelling by employing geologically recent plate velocities as surface boundary conditions (e.g., Bunge et al., 1998; McNamara and Zhong, 2005). In dynamical models that lack a thermochemical component, plumes tend to organize into clustered networks of thin upwellings (plume clusters) that form away from downwelling regions (e.g., Schubert et al., 2004; McNamara and Zhong, 2005). Although current research is assessing whether regions of plume clusters may resemble the large, low-velocity anomalies in the lowermost mantle when viewed through the blurred "eyes" of seismic tomography (Ritsema et al., 2007), it appears that thermochemical models of mantle convection provide the best explanation for the existence of the LLSVPs.

Thermochemical conceptual models that strive to explain the dynamics related to LLSVPs beneath Africa and the Pacific typically fall into two categories. Both invoke a large volume of anomalously dense mantle material; however, they differ in terms of the relative buoyancy and geologic longevity of the chemical anomaly.

The superplume hypothesis typically describes the large, low-velocity anomalies as being due to the presence of large, upward-doming plumes of the more-dense material (e.g., Davaille, 1999; Forte and Mitrovica, 2001; Davaille et al., 2002, 2005). These models are characterized by the denser component having a net positive buoyancy (the thermal buoyancy exceeds the negative buoyancy associated with the intrinsic density anomaly) such that it becomes unstable and forms large superplumes that are currently rising in the mantle. It has been shown (e.g., Davaille et al., 2002) that these structures may rise and sink many times before ultimately being well mixed into the background mantle. Smaller-scale thermal plumes can originate from the tops of these large domes, entraining some of the chemically distinct material in the dense dome. This entrainment may, in turn, explain the anomalous chemistry observed at ocean island basalts (OIBs; e.g., Hofmann, 1997, Fitton, this volume). One aspect of this model is that the present instance in Earth's history has the more-dense material actively rising, as opposed to other times in the past in which this material was either a stratified layer or sinking after a previous ascent.

Another, similar superplume phenomenon observed in geodynamical modeling involves the presence of long-lived, stable superplumes (McNamara and Zhong, 2004a). If the anomalously dense mantle component has a higher intrinsic viscosity (~100×) than the less-dense material, it may form large dome structures that migrate laterally across the lower mantle. These structures can maintain a vertical height, and they do not experience the rising and sinking observed in laboratory studies (e.g., Davaille et al., 2002). However, it is difficult to put forth a mineral physics explanation that would provide the necessary intrinsic viscosity increase to the dense material, so such a model is not favored here.

Although the basic superplume model remains a viable hypothesis, here we focus on the second category of thermochemical mantle hypotheses, which involve the presence of long-lived, stable, dense piles of chemically distinct material (e.g., Christensen and Hofmann, 1994; Tackley 1998, 2002; Kellogg et al., 1999; Jellinek and Manga, 2002, 2004; Ni et al., 2002; McNamara and Zhong, 2004a,b, 2005; Nakagawa and Tackley, 2005; Tan and Gurnis, 2005). In these models, piles of dense material maintain a near-neutral (slightly negative) buoyancy, and as a result, they are passively swept aside by downwelling flow and are focused beneath upwelling regions. Piles tend to form large, ridge-like structures that have thermal plumes originating from their peaks that entrain a small fraction of the more-dense material.

McNamara and Zhong (2005) performed numerical thermochemical calculations in a 3-D spherical geometry with Earth's recent plate history imposed as surface boundary conditions (120 m.y. over eleven stages of plate motions, as provided by Lithgow-Bertelloni and Richards 1998). The calculation employed the Boussinesq approximation with constant thermodynamic properties; however, depth-dependent thermal conductivity was explored and found to have only a minimal effect on the resulting thermal and chemical structures. A depth- and temperature-dependent rheology that included a thirty-fold increase across the transition zone was used. The initial condition included a flat, 255-km-thick more-dense layer and a steady-state temperature field derived from an axisymmetric thermochemical calculation. The imposed plate history acted to guide the formation of downwellings in historical subduction regions, which resulted in the focusing of the lower-mantle dense material into piles beneath Africa and the Pacific. These are the same regions characterized by the observed LLSVPs (see Fig. 3A and D). This modeling demonstrated that it is dynamically feasible that global flow patterns derived from the history of subduction can focus a dense component into thermochemical structures that, to first order, resemble the present-day LLSVP configuration.

Our preferred interpretation of LLSVPs is that they are large, dense thermochemical piles stabilized by upwelling currents that are downwelling-induced return flow. The temperature within and around the pile depends on several uncertain factors, like thermal conductivity and the degree of viscous heating. If we assume that deep-mantle piles have some temporal stability, then it is reasonable to assume they are denser than surrounding mantle (e.g., at a minimum, 2–5% denser). This assumption is consistent with the suggestion from some seismic studies of increased density in these locations (Ishii and Tromp, 2004; Trampert et al., 2004). The possibility of Fe-enrichment in D″ would decrease shear velocity and result in density elevation, so the chemical heterogeneity could be residual material from the core-formation process or accumulation of core-mantle reaction products. Subducted mid-ocean ridge basalt (MORB) is also expected to be denser than surrounding material at lower-mantle conditions and thus may account for the dense LLSVPs, assuming that MORB has accumulated progressively in the lowermost mantle (Hirose et al., 1999; Ohta et al., 2007)

The detailed structure (e.g., topography) of the sides and top of chemically distinct LLSVP material can play a significant role in the style and morphology of local upwelling currents and plume initiation (e.g., Jellinek and Manga, 2002, 2004; McNamara and Zhong, 2005). Numerical calculations show upward convective return flow guided by the LLSVP margins. Basal heating and internal flow of the LLSVP cause the boundaries between the surrounding mantle and LLSVP to be particularly hot (see Fig. 3B). If partial melt is indeed the origin of ULVZ structure, we would expect the edges of LLSVP structure to have the highest occurrence of ULVZ structure. As previously mentioned, the geographical distribution of ULVZ structure at present is not known in great enough detail to document such a spatial correlation. It is noteworthy, however, that two recent high-resolution studies detailing ULVZ structure are both near (and within) LLSVP margins: a double-array stacking study of ScS (a core-reflected S-wave) beneath the northern margin of the LLSVP beneath the Pacific Ocean (Avants et al., 2006; Lay et al., 2006), and a multiple vespagram analysis of ScP (an S-wave that converts to a P-wave upon reflection at the CMB) beneath the southwest margin of the same LLSVP (Rost et al., 2005, 2006). The strongest lateral gradients in tomographically derived V_S structures are near the margins of the LLSVPs (consistent with pile "edges"), and these regions of strong gradients are found to statistically correlate with surface hotspot locations (Thorne et al., 2004).

These findings are consistent with the conceptual model put forth in Figures 3C and 4. Large thermochemical piles are deflected away from downwellings by subduction currents and are swept to concentrate beneath upwelling return flow. LLSVP piles may thus be the key to the long-term history of subduction. LLSVP topographical features near their margins guide upwelling and serve as sites of thermal boundary layer instabili-

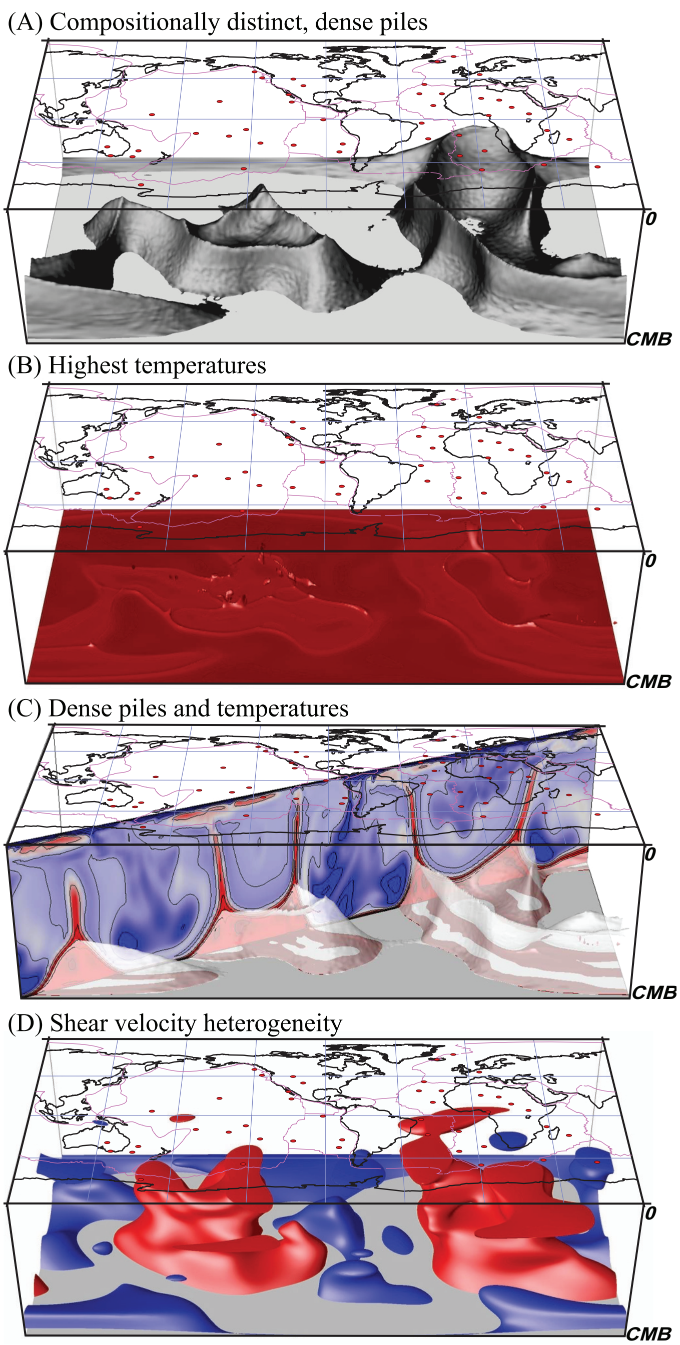

Figure 3. Continents, plate boundaries, and hotspots are shown on maps at the top of four boxes that represent the area of the whole globe, and the volume of the mantle from the surface to the core-mantle boundary (CMB). (A) Compositionally distinct, dense piles from the geodynamic calculation of McNamara and Zhong (2005). (B) The locations of the hottest temperatures in the mantle for the calculation of panel A are shown. Isotemperature contour is 0.98 for the calculation that spans temperatures from 0 to 1. The hottest temperatures are within the piles and are typically near the edges. (C) A temperature cross-section is shown, along with the piles from panel A in a transparent gray, and the hottest CMB temperatures of panel B are included (faint red stripes within the piles). Pile topography guides plume upwellings. (D) Shear velocity heterogeneity from Ritsema and van Heijst (2000) filtered to maximum spherical harmonic degree l = 8, with iso-velocity contours at -0.3% (red) and 0.5% (blue). Dense piles in the geodynamic calculation of panel A are geographically distributed similarly to the low velocities (red) in panel D.

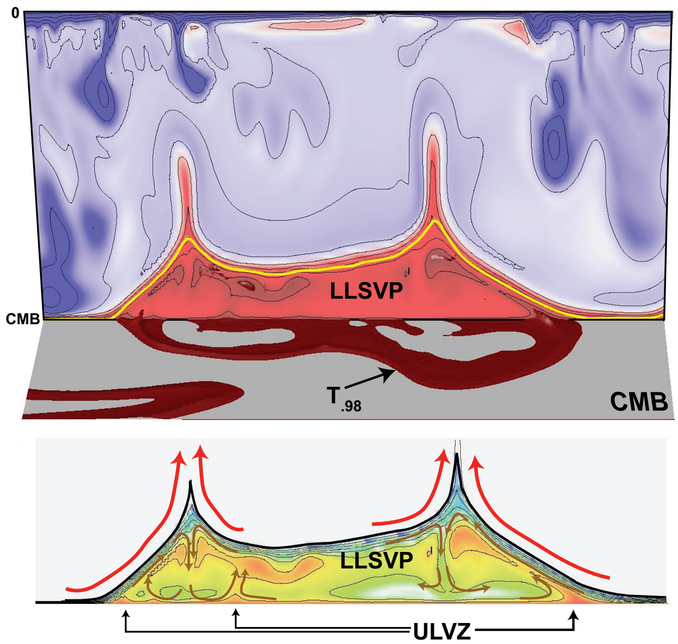

Figure 4. A close-up of the thermochemically dense pile beneath the Pacific Ocean in Figure 3A. (A) A cross-section from the surface to the core-mantle boundary (CMB) displays temperature variations, with the yellow line denoting the boundary of the chemically distinct material in the pile. We identify the thermochemical anomaly as the large low–shear velocity province (LLSVP). Part of the CMB surface is shown in front of the cross-section, along with an isotemperature contour (at 0.98, as in Fig. 3). (B) The same cross-section, but only the pile, with a more expanded color scale (colors span T = 0.7 to 1.0). Convective motions are indicated by the arrows. The hottest zones may invoke partial melt of LLSVP material, either at the CMB (denoted as an ultra-low velocity zone [ULVZ] in the figure), or in some isolated locations farther up within the LLSVP.

ties. Ascending plumes from the LLSVP margins may carry distinct chemical tracers from the deep mantle and CMB. OIB geochemistry for major hotspots favors recycled slab material as a significant source (e.g., Hofmann, 1997), which is consistent with past and/or ongoing subduction of slabs to the base of mantle and concentration of slab materials into the piles (e.g., Christensen and Yuen, 1984; Hager et al., 1985; Hutko et al., 2006). Thus, LLSVPs can be viewed as a by-product of whole-mantle convection, with physical segregation of dense material in the boundary layer. This process could occur today even if slabs temporarily go stagnant in the transition zone because of the difficulty of penetrating the 670-km phase boundary (Mitrovica and Forte, 1997) before they avalanche into the lower mantle. Of course, not all slab material has to penetrate into the deep mantle, and the LLSVPs may be comprised of slab material subducted long ago.

Seismological evidence for reflections down to 1000 km beneath southwest Pacific subduction zones is consistent with the penetration of MORB-bearing material into the lower mantle (Rost et al., 2007). Sequestration of dense MORB material (e.g., Hirose et al., 1999; Tan and Gurnis, 2005; Ohta et al., 2007) may account for the chemically distinct nature of the LLSVP material. This concept certainly requires geochemical assessment, as it is the only approach to establishing the temporal isolation of the LLSVP reservoir.

CONCLUSIONS

Recent deep-mantle seismological findings give rise to the hypothesis that any deep mantle plumes will originate near the margins of LLSVPs at the base of the mantle. Chemically distinct and dense LLSVP piles may be organized underneath large-scale upwellings associated with return flow from subduction-induced downwellings. The margins of the LLSVP at the CMB are the hottest locations in the mantle and may contain partial melt at the CMB that is imaged as ULVZ structure. The LLSVP and ULVZ structures may contain important isotopic signatures that become entrained in plumes that rise from boundary layer instabilities on the LLSVP margins. The recent data and models do not demonstrate that whole-mantle plumes exist. However, the emerging understanding of lower-mantle structure and processes does provide guidance as to where and why any plume rising from the deep mantle will originate, and how they may sample thermally and chemically distinct source regions other than right at the CMB.

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REFERENCES CITED

Avants, M., Lay, T., and Garnero, E.J., 2006, A new probe of ULVZ S-wave velocity structure: Array stacking of ScS waveforms: Geophysical Research Letters, v. 33, p. L07314, doi: 10.1029/2005GL024989.

Becker, T.W., and Boschi, L., 2002, A comparison of tomographic and geodynamic mantle models: Geochemistry, Geophysics, and Geosystems, v. 3, doi: 2001GC000168.

Bréger, L., and Romanowicz, B., 1998, Thermal and chemical 3D heterogeneity in D″: Science, v. 282, p. 718–720, doi: 10.1126/science.282.5389.718.

Buffett, B.A., 2002, Estimates of heat flux in the deep mantle based on the power requirements for the geodynamo: Geophysical Research Letters, v. 29, doi: 10.1029/2001GL014649.

Bunge, H.-P., Richards, M.A., Lithgow-Bertelloni, C., Baumgardner, J.R., Grand, S.P., and Romanowicz, B.A., 1998, Time scales and heterogeneous structure in geodynamic Earth models: Science, v. 280, p. 91–95.

Christensen, U.R., and Hofmann, A.W., 1994, Segregation of subducted oceanic crust in the convecting mantle: Journal of Geophysical Research, v. 99, p. 19,867–19,884, doi: 10.1029/93JB03403.

Christensen, U.R., and Yuen, D.A., 1984, The interaction of a subducting lithospheric slab with a chemical or phase boundary: Journal of Geophysical Research, v. 89, p. 4389–4402.

Courtillot, V., Davaille, A., Baesse, J., and Stock, J., 2003, Three distinct types of hotspots in the Earth's mantle: Earth and Planetary Science Letters, v. 205, p. 295–308, doi: 10.1016/S0012-821X(02)01048-8.

Cserepes, L., and Yuen, D.A., 2000, On the possibility of a second kind of mantle plume: Earth and Planetary Science Letters, v. 183, p. 61–71, doi: 10.1016/S0012-821X(00)00265-X.

Dahlen, F.A., 2004, Resolution limit of traveltime tomography: Geophysical Journal International, v. 157, p. 315–331, doi: 10.1111/j.1365-246X.2004.02214.x.

Dahlen, F.A., and Nolet, G., 2005, Comment on "On sensitivity kernels for wave equation transmission tomography": Geophysical Journal International, v. 163, p. 949–951.

Davaille, A., 1999, Simultaneous generation of hotspots and superswells by convection in a heterogeneous planetary mantle: Nature, v. 402, p. 756–760, doi: 10.1038/45461.

Davaille, A., Girard, F., and Le Bars, M., 2002, How to anchor hotspots in a convecting mantle?: Earth and Planetary Science Letters, v. 203, p. 621–634, doi: 10.1016/S0012-821X(02)00897-X.

Davaille, A., Stutzmann, E., Silveira, G., Besse, J., and Courtillot, V., 2005, Convective patterns under the Indo-Atlantic box: Earth and Planetary Science Letters, v. 239, p. 233–252, doi: 10.1016/j.epsl.2005.07.024.

Davies, G.F., 1990, Mantle plumes, mantle stirring, and hotspot chemistry: Earth and Planetary Science Letters, v. 99, p. 94–109, doi: 10.1016/0012-821X(90)90073-7.

de Hoop, M.V., and van der Hilst, R.D., 2005, Reply to comment by F.A. Dahlen and G. Nolet: Geophysical Journal International, v. 163, p. 952–955.

Dziewonski, A.M., 1984, Mapping the lower mantle—Determination of lateral heterogeneity in P-velocity up to degree and order 6: Journal of Geophysical Research, v. 89, p. 5929–5942.

Earle, P.S., and Shearer, P.M., 2001, Distribution of fine-scale mantle heterogeneity from observations of Pdiff coda: Bulletin of the Seismological Society of America, v. 91, p. 1875–1881, doi: 10.1785/0120000285.

Farnetani, C.G., 1997, Excess temperature of mantle plumes: The role of chemical stratification across D″: Geophysical Research Letters, v. 24, p. 1583–1586, doi: 10.1029/97GL01548.

Farnetani, C.G., and Richards, M.A., 1994, Numerical investigations of the mantle plume initiation model for flood basalt events: Journal of Geophysical Research, v. 99, p. 13,813–13,833, doi: 10.1029/94JB00649.

Farnetani, C.G., and Samuel, H., 2005, Beyond the thermal plume paradigm: Geophysical Research Letters, v. 32, p. L07311, doi: 1029/2005GL022360.

Fitton, J.G., 2007 (this volume), The OIB paradox, *in* Foulger, G.R., and Jurdy, D.M., eds., Plates, plumes, and planetary processes: Boulder, Colorado, Geological Society of America Special Paper 430, doi: 10.1130/2007.2430(20).

Ford, S.R., Garnero, E.J., and McNamara, A.K., 2006, A strong lateral shear velocity gradient and anisotropy heterogeneity in the lowermost mantle beneath the southern Pacific: Journal of Geophysical Research, v. 111, p. B03306, doi: 10.1029/2004JB003574.

Forte, A.M., and Mitrovica, J.X., 2001, Deep-mantle high viscosity flow and thermochemical structure inferred from seismic and geodynamic data: Nature, v. 410, p. 1049–1056, doi: 10.1038/35074000.

Foulger, G.R., and Pearson, D.G., 2001, Is Iceland underlain by a plume in the lower mantle? Seismology and helium isotopes: Geophysical Journal International, v. 145, p. F1–F5, doi: 10.1046/j.0956-540x.2001.01457.x.

Foulger, G.R., Pritchard, M.J., Julian, B.R., Evans, J.R., Allen, R.M., Nolet, G., Morgan, W.J., Bergsson, B.H., Rlendsson, P., Jakobsdottir, S., Ragnarsson, S., Stefansson, R., and Vogfjörd, K., 2001, Seismic tomography shows that upwelling beneath Iceland is confined to the upper mantle: Geophysical Journal International, v. 146, p. 504–530, doi: 10.1046/j.0956-540x.2001.01470.x.

Garnero, E.J., Revenaugh, J., Williams, Q., Lay, T., and Kellogg, L.H., 1998, Ultralow velocity zone at the core-mantle boundary, *in* Gurnis, M., et al., eds., The core-mantle boundary region: Washington D.C., American Geophysical Union, p. 319–334.

Garnero, E.J., Maupin, V., Lay, T., and Fouch, M.J., 2004, Variable azimuthal anisotropy in Earth's lowermost mantle: Science, v. 306, p. 259–261, doi: 10.1126/science.1103411.

Grand, S.P., 2002, Mantle shear-wave tomography and the fate of subducted slabs: Philosophical Transactions of the Royal Society of London A, v. 360, p. 2475–2491.

Gu, Y.J., Dziewonski, A.M., Su, W.J., and Ekström, G., 2001, Models of the mantle shear velocity and discontinuities in the pattern of lateral heterogeneities: Journal of Geophysical Research, v. 106, p. 11,169–11,199, doi: 10.1029/2001JB000340.

Hager, B.H., Clayton, R.W., Richards, M.A., Comer, R.P., and Dziewonski, A.M., 1985, Lower mantle heterogeneity, dynamic topography and the geoid: Nature, v. 313, p. 541–546, doi: 10.1038/313541a0.

He, Y., Wen, L., and Zheng, T., 2006, Geographic boundary and shear wave velocity structure of the "Pacific anomaly" near the core-mantle boundary beneath western Pacific: Earth and Planetary Science Letters, v. 244, p. 302–314, doi: 10.1016/j.epsl.2006.02.007.

Hedlin, M.A.H., and Shearer, P.M., 2000, An analysis of large-scale variations in small-scale mantle heterogeneity using Global Seismic Network recordings of precursors to PKP: Journal of Geophysical Research, v. 105, p. 13,655–13,673, doi: 10.1029/2000JB900019.

Helmberger, D.V., Wen, L., and Ding, X., 1998, Seismic evidence that the source of the Iceland hotspot lies at the core-mantle boundary: Nature, v. 396, p. 251–255, doi: 10.1038/24357.

Helmberger, D.V., Ni, S., Wen, L., and Ritsema, J., 2000, Seismic evidence for ultra low velocity zones beneath Africa and the Atlantic Ocean: Journal of Geophysical Research, v. 105, p. 23,865–23,878, doi: 10.1029/2000JB900143.

Hernlund, J.W., Thomas, C., and Tackley, P.J., 2005, A doubling of the post-perovskite phase boundary and the structure of the lowermost mantle: Nature, v. 434, p. 882–886, doi: 10.1038/nature03472.

Hirose, K., 2006, Postperovskite phase transition and its geophysical implications: Reviews of Geophysics, v. 44, p. RG3001, doi: 10.1029/2005RG000186.

Hirose, K., Fei, Y., Ma, Y., and Mao, H.-K., 1999, The fate of subducted basaltic crust in the Earth's lower mantle: Nature, v. 397, p. 53–56, doi: 10.1038/16225.

Hirose, K., Karato, S.-I., Cormier, V.F., Brodholt, J.P., and Yuen, D.A., 2006, Unsolved problems in the lowermost mantle: Geophysical Research Letters, v. 33, p. L12S01, doi:10.1029/2006GL025691.

Hofmann, A.W., 1997, Mantle geochemistry: The message from oceanic volcanism: Nature, v. 385, p. 219–229, doi: 10.1038/385219a0.

Hutko, A., Lay, T., Garnero, E.J., and Revenaugh, J.S., 2006, Seismic detection of folded, subducted lithosphere at the core-mantle boundary: Nature, v. 441, p. 333–336, doi: 10.1038/nature04757.

Ishii, M., and Tromp, J., 1999, Normal-mode and free-air gravity constraints on lateral variations in velocity and density of Earth's mantle: Science, v. 285, p. 1231–1236, doi: 10.1126/science.285.5431.1231.

Ishii, M., and Tromp, J., 2004, Constraining large-scale mantle heterogeneity using mantle and inner-core sensitive normal modes: Physics of the Earth and Planetary Interiors, v. 146, p. 113–124, doi: 10.1016/j.pepi.2003.06.012.

Jellinek, A.M., and Manga, M., 2002, The influence of a chemical boundary layer on the fixity, spacing, and lifetime of mantle plumes: Nature, v. 418, p. 760–763, doi: 10.1038/nature00979.

Jellinek, A.M., and Manga, M., 2004, Links between long-lived hot spots, mantle plumes, D″, and plate tectonics: Reviews of Geophysics, v. 42, doi: 10.1029/2003RG000144.

Ji, Y., and Nataf, H.-C., 1998, Detection of mantle plumes in the lower mantle by diffraction tomography: Hawaii: Earth and Planetary Science Letters, v. 159, p. 99–115, doi: 10.1016/S0012-821X(98)00060-0.

Kárason, H., and van der Hilst, R.D., 2001, Tomographic imaging of the lowermost mantle with differential times of refracted and diffracted core phases (PKP, Pdiff): Journal of Geophysical Research, v. 106, p. 6569–6588, doi: 10.1029/2000JB900380.

Karki, B.B., Wentzcovitch, R.M., de Gironcoli, S., and Baroni, S., 1999, First-principles determination of elastic anisotropy and wave velocities of MgO at lower mantle conditions: Science, v. 286, p. 1705–1709, doi: 10.1126/science.286.5445.1705.

Kellogg, L.H., Hager, B.H., and van der Hilst, R.D., 1999, Compositional stratification in the deep mantle: Science, v. 283, p. 1881–1884, doi: 10.1126/science.283.5409.1881.

Kendall, J.-M., 2000, Seismic anisotropy in the boundary layers of the mantle, *in* Karato, S.-I., et al., eds., Earth's deep interior: Mineral physics and tomography from the atomic to the global scale: Washington, D.C., American Geophysical Union, p. 133–159.

Kendall, J.-M., and Silver, P.G., 1998, Investigating causes of D″ anisotropy, *in* Gurnis, M., et al., eds., The core-mantle boundary region: Washington, D.C., American Geophysical Union, p. 97–118.

Kuo, C., and Romanowicz, B., 2002, On the resolution of density anomalies in the Earth's mantle using spectral fitting of normal mode data: Geophysical Journal International, v. 150, p. 162–179, doi: 10.1046/j.1365-246X.2002.01698.x.

Lay, T., 2005, The deep mantle thermo-chemical boundary layer: The putative mantle plume source, *in* Foulger, G.R., et al., eds., Plates, plumes and paradigms: Boulder, Colorado, Geological Society of America Special Paper 388, p. 193–205.

Lay, T., Garnero, E.J., Williams, Q., Kellogg, L., and Wysession, M.E., 1998, Seismic wave anisotropy in the D″ region and its implications, *in* Gurnis, M., et al., eds., The core-mantle boundary region: Washington, D.C., American Geophysical Union, p. 299–318.

Lay, T., Heinz, E., Ishii, M., Shim, S.H., Tsuchiya, T., Tsuchiya, J., Wentzcovich, R., and Yuen, D., 2005, Multidisciplinary impact of the lower mantle perovskite phase transition: Transactions of the American Geophysical Union, v. 86, p. 1–5.

Lay, T., Hernlund, J., Garnero, E.J., and Thorne, M.S., 2006, A post-perovskite lens and D″ heat flux beneath the central Pacific: Science, v. 314, p. 1272–1276, doi: 10.1126/science.1133280.

Lin, S., and van Keken, P.E., 2005, Multiple volcanic episodes of flood basalts caused by thermochemical mantle plumes: Nature, v. 436, p. 250–252, doi: 10.1038/nature03697.

Lithgow-Bertelloni, C., and Richards, M.A., 1998, The dynamics of Cenozoic and Mesozoic plate motions: Reviews of Geophysics, v. 36, p. 27–78, doi: 10.1029/97RG02282.

Luo, S.-N., Ni, S., and Helmberger, D.V., 2001, Evidence for a sharp lateral variation of velocity at the core-mantle boundary from multipathed PKPab: Earth and Planetary Science Letters, v. 189, p. 155–164, doi: 10.1016/S0012-821X(01)00364-8.

Mainprice, D., Barruol, G., and Ben Ismail, W., 2000, The seismic anisotropy of the Earth's mantle: From single crystal to polycrystal, *in* Karato, S.-I., et al., eds., Earth's deep interior: Mineral physics and tomography from the atomic to the global scale: Washington, D.C., American Geophysical Union, p. 237–264.

Masters, G., and Gubbins, D., 2003, On the resolution of density within the Earth: Physics of the Earth and Planetary Interiors, v. 140, p. 159–167, doi: 10.1016/j.pepi.2003.07.008.

Masters, G., Laske, G., Bolton, H., and Dziewonski, A.M., 2000, The relative behavior of shear velocity, bulk sound speed, and compressional velocity in the mantle: Implications for chemical and thermal structure, *in* Karato, S.-I., et al., eds., Earth's deep interior: Mineral physics and tomography from the atomic to the global scale: Washington, D.C., American Geophysical Union, p. 63–87.

McNamara, A.K., and Zhong, S., 2004a, Thermochemical structures within a spherical mantle: Superplumes or piles?: Journal of Geophysical Research, v. 109, p. B07402, doi: 10.1029/2003JB002847.

McNamara, A.K., and Zhong, S., 2004b, The influence of thermochemical convection on the fixity of mantle plumes: Earth and Planetary Science Letters, v. 222, p. 485–500, doi: 10.1016/j.epsl.2004.03.008.

McNamara, A.K., and Zhong, S., 2005, Thermochemical piles under Africa and the Pacific: Nature, v. 437, p. 1136–1139, doi: 10.1038/nature04066.

McNamara, A.K., Karato, S.-I., and van Keken, P.E., 2001, Localization of dislocation creep in the lower mantle: Implications for the origin of seismic anisotropy: Earth and Planetary Science Letters, v. 191, p. 85–99, doi: 10.1016/S0012-821X(01)00405-8.

McNamara, A.K., van Keken, P.E., and Karato, S.-I., 2002, Development of anisotropic structure in the Earth's lower mantle by solid-state convection: Nature, v. 416, p. 310–314, doi: 10.1038/416310a.

McNamara, A.K., van Keken, P.E., and Karato, S.-I., 2003, Development of finite strain in the convecting lower mantle and its implications for seismic anisotropy: Journal of Geophysical Research, v. 108, p. 2230, doi: 10.1029/2002JB001970.

Mégnin, C., and Romanowicz, B., 2000, The shear velocity structure of the mantle from the inversion of body, surface, and higher modes waveforms: Geophysical Journal International, v. 143, p. 709–728, doi: 10.1046/j.1365-246X.2000.00298.x.

Mitrovica, J.X., and Forte, A.M., 1997, Radial profile of mantle viscosity: Results from joint inversion of convection and post-glacial rebound observables: Journal of Geophysical Research, v. 102, p. 2751–2769, doi: 10.1029/96JB03175.

Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., Engdahl, E., and Hung, S., 2004, Finite-frequency tomography reveals a variety of plumes in the mantle: Science, v. 303, p. 338–343, doi: 10.1126/science.1092485.

Montelli, R., Nolet, G., Dahlen, F.A., and Masters, G., 2006, A catalogue of deep mantle plumes: New results from finite-frequency tomography: Geochemistry, Geophysics, and Geosystems, v. 7, p. Q11007, doi: 10.1029/2006GC001248.

Morgan, W.J., 1971, Convection plumes in the lower mantle: Nature, v. 230, p. 42–43, doi: 10.1038/230042a0.

Murakami, M., Hirose, K., Kawamura, K., Sata, N., and Ohishi, Y., 2004, Post-perovskite phase transition in $MgSiO_3$: Science, v. 304, p. 855–858, doi: 10.1126/science.1095932.

Nakagawa, T., and Tackley, P.J., 2005, The interaction between the post-perovskite phase change and a thermo-chemical boundary layer near the core-mantle boundary: Earth and Planetary Science Letters, v. 238, p. 204–216, doi: 10.1016/j.epsl.2005.06.048.

Nataf, H.-C., 2000, Seismic imaging of mantle plumes: Annual Review of Earth and Planetary Sciences, v. 28, p. 391–417, doi: 10.1146/annurev.earth.28.1.391.

Ni, S., and Helmberger, D.V., 2001, Horizontal transition from fast (slab) to slow (plume) structures at the core-mantle boundary: Earth and Planetary Science Letters, v. 187, p. 301–310, doi: 10.1016/S0012-821X(01)00273-4.

Ni, S., and Helmberger, D.V., 2003a, Seismological constraints on the South African superplume; Could be the oldest distinct structure on Earth: Earth and Planetary Science Letters, v. 206, p. 119–131, doi: 10.1016/S0012-821X(02)01072-5.

Ni, S., and Helmberger, D.V., 2003b, Ridge-like lower mantle structure beneath South Africa: Journal of Geophysical Research, v. 108, p. 2094, doi: 10.1029/2001JB001545.

Ni, S., Tan, E., Gurnis, M., and Helmberger, D.V., 2002, Sharp sides to the African superplume: Science, v. 296, p. 1850–1852, doi: 10.1126/science.1070698.

Oganov, A.R., and Ono, S., 2004, Theoretical and experimental evidence for a post-perovskite phase of $MgSiO_3$ in Earth's D″ layer: Nature, v. 430, p. 445–448, doi: 10.1038/nature02701.

Ohta, K., Hirose, K., Lay, T., Sata, N., and Ohishi, Y., 2007, Evidence for a MORB-rich pile above the Earth's core-mantle boundary: Proceedings of the National Academy of Sciences, USA, in press.**[AQ1]**

Olson, P., and Kincaid, C., 1991, Experiments on the interaction of thermal convection and compositional layering at the base of the mantle: Journal of Geophysical Research, v. 96, p. 4347–4354.

Revenaugh, J.S., and Meyer, R., 1997, Seismic evidence of partial melt within a possibly ubiquitous low-velocity layer at the base of the mantle: Science, v. 277, p. 670–673, doi: 10.1126/science.277.5326.670.

Ritsema, J., and van Heijst, H.J., 2000, Seismic imaging of structural heterogeneity in Earth's mantle: Evidence for large-scale mantle flow: Science Progress, v. 83, p. 243–259.

Ritsema, J., McNamara, A.K., and Bull, A.L., 2007, Tomographic filtering of geodynamic models: Implications for model interpretation and large-scale mantle structure: Journal of Geophysical Research, v. 112, p. B01303, doi: 10.1029/2006JB004566.

Rokosky, J., Lay, T., and Garnero, E.J., 2006, Small-scale lateral variations in azimuthally anisotropic D″ structure beneath the Cocos plate: Earth and Planetary Science Letters, v. 248, p. 411–425, doi: 10.1016/j.epsl.2006.06.005.

Romanowicz, B., 2001, Can we resolve 3D density heterogeneity in the lower mantle?: Geophysical Research Letters, v. 28, p. 1107–1110.

Rost, S., and Revenaugh, J.S., 2001, Seismic detection of rigid zones at the top of the core: Science, v. 294, p. 1911–1914, doi: 10.1126/science.1065617.

Rost, S., Garnero, E.J., Williams, Q., and Manga, M., 2005, Seismic constraints on a possible plume root at the core-mantle boundary: Nature, v. 435, p. 666–669, doi: 10.1038/nature03620.

Rost, S., Garnero, E.J., and Williams, Q., 2006, Fine scale ultra-low velocity zone structure from high-frequency seismic array data: Journal of Geophysical Research, v. 111, p. B09310, doi: 10.1029/2005JB004088.

Rost, S., Garnero, E.J., and Williams, Q., 2007, Seismic array detection of subducted oceanic crust in the lower mantle: Earth and Planetary Science Letters, in press.**[AQ2]**

Russell, S.A., Lay, T., and Garnero, E.J., 1998, Seismic evidence for small-scale dynamics in the lowermost mantle at the root of the Hawaiian hotspot: Nature, v. 396, p. 255–258, doi: 10.1038/24364.

Schubert, G., Masters, G., Olson, P., and Tackley, P.J., 2004, Superplumes or plume clusters?: Physics of the Earth and Planetary Interiors, v. 146, p. 147–162, doi: 10.1016/j.pepi.2003.09.025.

Sleep, N.H., 2007 (this volume), Origins of the plume hypothesis and some of its implications, *in* Foulger, G.R., and Jurdy, D.M., eds., Plates, plumes, and planetary processes: Boulder, Colorado, Geological Society of America Special Paper 430, doi: 10.1130/2007.2430(02).

Steinberger, B., 2000, Plumes in a convecting mantle: Models and observations for individual hotspots: Journal of Geophysical Research, v. 105, p. 11,127–11,152, doi: 10.1029/1999JB900398.

Stixrude, L., 1998, Elastic constants and anisotropy of $MgSiO_3$ perovskite, periclase, and SiO_2 at high pressure, *in* Gurnis, M., et al., eds., The core-mantle boundary region: Washington, D.C., American Geophysical Union, p. 83–96.

Su, W.J., and Dziewonski, A.M., 1997, Simultaneous inversion for 3-D variations in shear and bulk velocity in the mantle: Physics of the Earth and Planetary Interiors, v. 100, p. 135–156, doi: 10.1016/S0031-9201(96)03236-0.

Tackley, P.J., 1998, Three-dimensional simulations of mantle convection with a thermochemical CMB boundary layer: D″?, *in* Gurnis, M., et al., eds., The core-mantle boundary region: Washington, D.C., American Geophysical Union, p. 231–253.

Tackley, P.J., 2002, Strong heterogeneity caused by deep mantle layering: Geochemistry, Geophysics, and Geosystems, v. 3, p. 1024, doi: 10.1029/2001GC000167.

Tan, E., and Gurnis, M., 2005, Metastable superplumes and mantle compressibility: Geophysical Research Letters, v. 32, p. L20307, doi: 10.1029/2005GL024190.

Thorne, M., and Garnero, E.J., 2004, Inferences on ultralow-velocity zone structure from a global analysis of SPdKS waves: Journal of Geophysical Research, v. 109, p. B08301, doi: 10.1029/2004JB003010.

Thorne, M., Garnero, E.J., and Grand, S., 2004, Geographic correlation between hot spots and deep mantle lateral shear-wave velocity gradients: Physics of the Earth and Planetary Interiors, v. 146, p. 47–63, doi: 10.1016/j.pepi.2003.09.026.

Tilmann, F.J., McKenzie, D., and Priestley, K.F., 1998, P and S wave scattering from mantle plumes: Journal of Geophysical Research, v. 103, p. 21,145–21,163, doi: 10.1029/98JB01070.

To, A., Romanowicz, B., Capdeville, Y., and Takeuchi, N., 2005, 3D effects of sharp boundaries at the borders of the African and Pacific superplumes: Observation and modeling: Earth and Planetary Science Letters, v. 233, p. 137–153, doi: 10.1016/j.epsl.2005.01.037.

Trampert, J., Deschamps, F., Resovsky, J., and Yuen, D.A., 2004, Probabilistic tomography maps chemical heterogeneities throughout the mantle: Science, v. 306, p. 853–856, doi: 10.1126/science.1101996.

Tsuchiya, T., Tsuchiya, J., Umemoto, K., and Wentzcovitch, R.M., 2004, Phase transition in $MgSiO_3$ perovskite in the Earth's lower mantle: Earth and Planetary Science Letters, v. 224, p. 241–248, doi: 10.1016/j.epsl.2004.05.017.

van der Hilst, R.D., Widyantoro, S., and Engdahl, E.R., 1997, Evidence for deep mantle circulation from global tomography: Nature, v. 386, p. 578–584, doi: 10.1038/386578a0.

van Keken, P.E., 1997, Evolution of starting mantle plumes: A comparison between numerical and laboratory models: Earth and Planetary Science Letters, v. 148, p. 1–11, doi: 10.1016/S0012-821X(97)00042-3.

Vidale, J.E., and Hedlin, M.A.H., 1998, Evidence for partial melt at the core-mantle boundary north of Tonga from the strong scattering of seismic waves: Nature, v. 391, p. 682–685, doi: 10.1038/35601.

Wang, Y., and Wen, L., 2004, Mapping the geometry and geographic distribution of a very-low velocity province at the base of the Earth's mantle: Journal of Geophysical Research, v. 109, p. B10305, doi: 10.1029/2003JB002674

Wen, L., 2000, Intense seismic scattering near the Earth's core-mantle boundary beneath the Comoros hotspot: Geophysical Research Letters, v. 27, p. 3627–3630, doi: 10.1029/2000GL011831.

Wen, L., 2006, A compositional anomaly at the Earth's core-mantle boundary as an anchor to the relatively slowly moving surface hotspots and as source to the DUPAL anomaly: Earth and Planetary Science Letters, v. 246, p. 138–148, doi: 10.1016/j.epsl.2006.04.024.

Wen, L., and Helmberger, D.V., 1998, Ultra-low velocity zones near the core-mantle boundary from broadband PKP precursors: Science, v. 279, p. 1701–1703, doi: 10.1126/science.279.5357.1701.

Wen, L., Silver, P., James, D., and Kuehnel, R., 2001, Seismic evidence for a thermo-chemical boundary layer at the base of the Earth's mantle: Earth and Planetary Science Letters, v. 189, p. 141–153, doi: 10.1016/S0012-821X(01)00365-X.

Wentzcovitch, R.M., Karki, B.B., Cococcioni, M., and de Gironcoli, S., 2004, Thermoelastic properties of $MgSiO_3$-perovskite: Insights on the nature of the Earth's lower mantle: Physical Review Letters, v. 92, p. 018501-1–018501-4, doi: 10.1103/PhysRevLett.92.018501.

Wessel, P., and Smith, W.H.F., 1998, New, improved version of Generic Mapping Tools released: Eos (Transactions, American Geophysical Union), v. 79, p. 579, doi: 10.1029/98EO00426.

Williams, Q., and Garnero, E.J., 1996, Seismic evidence for partial melt at the base of Earth's mantle: Science, v. 273, p. 1528–1530, doi: 10.1126/science.273.5281.1528.

Williams, Q., Revenaugh, J.S., and Garnero, E.J., 1998, A correlation between ultra-low basal velocities in the mantle and hot spots: Science, v. 281, p. 546–549, doi: 10.1126/science.281.5376.546.

Wookey, J., Kendall, J.-M., and Rumpker, G., 2005, D″ anisotropy from differential S-ScS splitting: Geophysical Journal International, v. 161, p. 829–838, doi: 10.1111/j.1365-246X.2005.02623.x.

Wysession, M.E., Bartkó, L., and Wilson, J.B., 1994, Mapping the lowermost mantle using core-reflected shear waves: Journal of Geophysical Research, v. 99, p. 13,667–13,684, doi: 10.1029/94JB00691.

Zhao, D., 2001, Seismic structure and origin of hotspots and mantle plumes: Earth and Planetary Science Letters, v. 192, p. 251–265, doi: 10.1016/S0012-821X(01)00465-4.

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