GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 17, PAGES 2777-2780, SEPTEMBER 1, 2000

Fuzzy Patches on the Earth's Core–Mantle Boundary?

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Abstract. Recent seismological investigations reveal the presence of highly anomalous structures at the base of the mantle, modeled as patches ≤ 5-50 km thick having ultralow–velocities ($-\delta V_P$~10-20%, $-\delta V_S$~10-50%). Waveform modeling shows seismological data are compatible with the patches exhibiting a wide range of density increases, up to $\delta\rho$~60%, which can be ascribed to chemical contamination of the deep mantle by the core. Not all anomalies require lowermost mantle partial melting, and may be located just below or right at the core–mantle boundary (CMB): a ~1-3 km thick zone of finite rigidity (crystallization?) at the top of the outer core or, more generally, of gradational properties across the CMB can also explain observations. Fuzzy patches at the boundary may be zones of intense chemical and physical interactions between the mantle and core.

1. Introduction

Detailed seismological investigations of Earth's interior have revealed the presence of thin patches of ultra-low velocity zones (ULVZ) in many locations at the base of the mantle. Previous work includes travel-time studies [*Sylvander and Souriau,* 1996; *Sylvander et al.,* 1997], waveform analyses of SP_dKS -- waves that have short segments of P wave diffraction along the CMB [*Garnero and Helmberger,* 1996, 1998; *Helmberger et al.*, 1998; *Wen and Helmberger,* 1998a], and studies of precursors to seismic phases reflected off of (PcP, ScP) or travelling through (PKP) the outer core [*Mori and Helmberger*, 1995; *Revenaugh and Meyer*, 1997; *Wen and Helmberger*, 1998b; *Vidale and Hedlin,* 1998; *Garnero and Vidale,* 1999]. Significant reductions in V_P and V_S have been invoked in these studies to match the observed waveforms: as much as $-\delta V_P \leq$ 5-20% and $-\delta V_S \leq$ 10-50%, spread out over a thickness of ~5-50 km. Such low-velocities are most plausibly interpreted in terms of partial molten just above the CMB [*Williams and Garnero*, 1996; *Wen and Helmberger*, 1998b; *Vidale and Hedlin,* 1998], which is compatible with interpretations of experimental results [*Holland and Ahrens,* 1997; *Zerr et al.*, 1998]. A correlation between the locations of hot spots and ULVZs has been noted [*Williams et al.,* 1998]. Less than 50% of the CMB has been probed for ULVZ, and just over 12% of the probed areas exhibit evidence for its presence. Also, for localized ULVZ patches (e.g., lateral scales < 500 km), strong variability is present in data for nearly coincident paths, suggesting significant heterogeneity in properties within each patch.

Paper number 2000GL008498.
0094-8276/00/2000GL008498$05.00

2. Modeling trade-offs

Although significant tradeoffs are recognized in ULVZ modeling, only a relatively narrow range of models satisfying the seismological observations have been explored to date. Detailed modeling of the SP_dKS waveform, allows a wide range of models to be evaluated. In particular, we consider the effects of perturbations in density (ρ) as well as wave velocities in modeling data. Broadband synthetic seismograms were calculated for the vertically-polarized shear (SV) component of displacement, using the one-dimensional reflectivity method [*Kind and Müller*, 1975]. The SP_dKS waveforms are analyzed relative to SKS.

Fig. 1 summarizes results for several models that match data obtained from the 3/31/94 Fiji event as recorded at North American broadband stations [*Garnero and Helmberger,* 1998]. Clearly, a range of ULVZ thicknesses (2-10 km), density perturbations (0-60%), and velocity perturbations can be found that match data. Similar conclusions are reached when modeling seismograms for other ULVZ patches.

A more comprehensive analysis of tradeoffs among ULVZ characteristics for the Fiji data set is summarized in Fig. 2. Models with 1:1 and 3:1 ratios in V_S:V_P reductions can both match the observations, the latter being what is predicted for partial melting [*Williams and Garnero,* 1996]. If no density drop is considered, the range of acceptable ULVZ thicknesses is between ~5 and 15 km, depending on assumed velocity reduction. Allowing for increases in ρ, however, results in further relative ULVZ thickness reductions being required to match data. The physical reason for this is that SP_dKS can be broadened by slightly later arriving internal reflections within

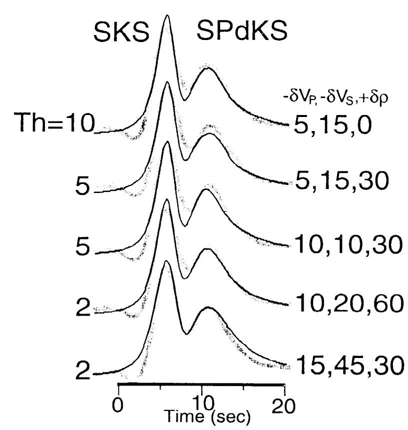

Figure 1. A broadband displacement record at 111° in distance (thick gray trace) is overlain on synthetics (thin traces) calculated for five selected combinations of ULVZ thickness, density and velocity perturbations that these all reproduce the timing and wave shape of SP_dKS and SKS.

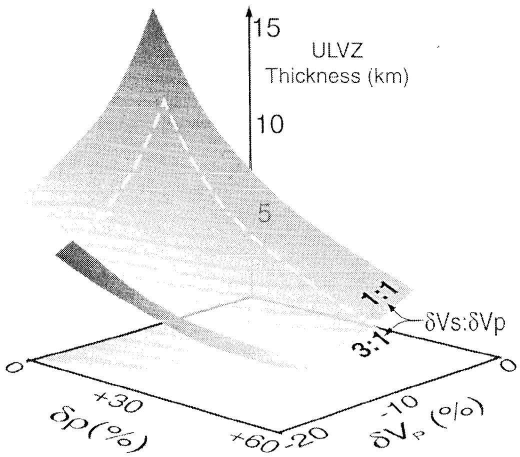

Figure 2. ULVZ modeling tradeoffs in thickness, density (δρ) and velocity (δV_P, δV_S) required to match SP_dKS waveforms of a Fiji event. Velocity and density combinations that model data are shown as solution sheets. Results for V_S and V_P perturbations with a ratio of δV_P:δV_S = 1:1 (top sheet) or 3:1 (bottom sheet) are shown.

the ULVZ layer, whose strength depends on the impedance contrast between the ULVZ and overlying mantle, as well as sharpness to the ULVZ top. More extreme magnitudes of velocity and density perturbations are associated with smaller values of thickness; for example, 1-3 km thicknesses can reproduce observed seismograms as long as they are also characterized by very low velocities ($-\delta V_P$~ 5-20%; $-\delta V_S$~10-50%). Thicknesses greater than 10-15 km with ($-\delta V_P$,$-\delta V_S$,δρ)=(10,30,0) produce an SKS precursor not seen in data [*Garnero and Helmberger*, 1998; *Stutzmann et al.*, 2000]; thus invoking the partial melt hypothesis requires either thinner layers, less extreme reductions, or ULVZ topography [e.g., *Hemberger et al.*, 1998].

3. ULVZ Density Considerations

The modeling results indicate the possibility of surprisingly large density increases of up to 60%. Such magnitudes seem to require a major variation in bulk composition across the depth of the lowermost mantle, but no phase transition having a density change greater than 10-15% has been identified for mantle minerals at lower-mantle conditions, and no transition has yet been found at the pressure–temperature conditions of the ULVZ for likely mantle minerals [*Vassiliou and Ahrens*, 1982; *Knittle and Jeanloz,* 1987; *Mao et al.*, 1991]. As the thermal expansion coefficient is expected to be less than 2×10^{-5} K^{-1} for the lowermost mantle, a temperature decrease of more than 10^4 K (far more than the temperature of the outer core) would be required in order to obtain a density increase of 20% or more. Chemical reactions at the CMB [*Knittle and Jeanloz,* 1989, 1991] could provide the necessary mechanism. Indeed, suggestions of compositional variations across the lowermost mantle based on the combined results of seismological and geodynamical modeling, as well as mineral physics considerations, are entirely compatible with our findings [*Manga and Jeanloz*, 1996; *van der Hilst and Karason*, 1999; *Kellogg et al.*, 1999]. The presence of dense metallic phases at the base of the mantle, which are the expected product of CMB reactions, can have a significant impact on the thermal and electromagnetic coupling between the mantle and core [*Knittle and Jeanloz,* 1989, 1991; *Jeanloz,* 1990; *Buffett*, 1996; *Manga and Jeanloz*, 1996; *Kellogg*, 1997; *Montague et al.*, 1998].

The interpretation of the ULVZ as resulting from chemical contamination (and reaction) of the lowermost mantle by the core is not in conflict with the identification of this zone as being a region of partial melting [*Williams and Garnero,* 1996; *Holland and Ahrens,* 1997; *Zerr et al.*, 1998]. One interpretation might even lead to the other, in that partial melting would make it especially easy for the lowermost mantle to react chemically with the core; by the same token, contamination by core metal could well induce melting at the base of the mantle. In this sense, the two hypotheses are mutually reinforcing. However, partial melting is not required for explaining all of the data, and is in some cases incompatible with a ULVZ containing large ρ anomalies.

Because seismic-wave velocities depend on the ratio of an elastic modulus to the density, the large increases in density shown in Fig. 2 can lead to conditions precluding melting in the ULVZ. The wave velocities are given by $V = [M/\rho]^{1/2}$ with M being the shear modulus (μ) and the longitudinal modulus ($K + 4\mu/3$: K is the bulk modulus) for, respectively, S and P waves. The relative variation in velocity is therefore given by $\delta\ln V = (1/2)\,[\delta\ln M - \delta\ln\rho]$. Because the shear modulus must decrease upon melting, $\delta\ln M < 0$ and there must be a decrease in wave velocity that is at least as large as half the density increase: $-\delta\ln V = (1/2)\delta\ln\rho - (1/2)\delta\ln M$. That is, $-\delta\ln V > (1/2)\delta\ln\rho$ for melting. Thus, melting is not possible if the magnitude of the velocity decrease is less than half that of the density increase. That is, for a sufficiently large density increase, the entire drop in velocity is due to the density; there is no possibility of the modulus having decreased, and an increase in modulus may even be required in order to match the velocity change. Because the elastic modulus must decrease upon melting, the relative magnitudes of velocity and density changes provide a criterion for whether or not melting takes place in the ULVZ. As is evident from Fig. 3, there is a wide range of acceptable model solutions for which melting is ruled out. These correspond to conditions involving the most extreme perturbations in velocities and density, along with the small values of thickness (< 3-7 km).

As the contrast in density and seismic velocities is larger across the CMB than for any other boundary on Earth (including the surface), one might wonder if small perturbations of the mantle–core interface can explain the ULVZ signature as well as is done by invoking large changes in the properties of the lowermost mantle. One end-member

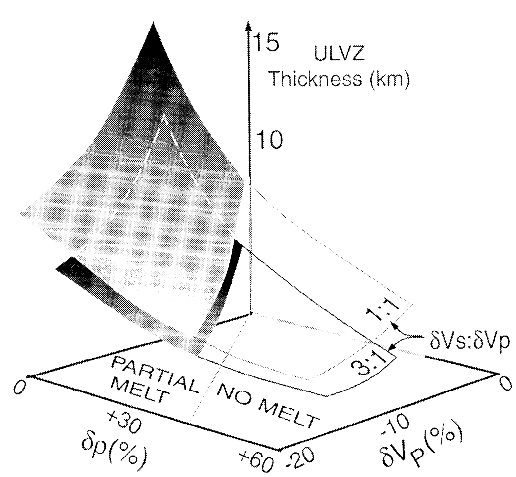

Figure 3. As in Fig. 2, but distinguishing ranges of values that are compatible with partial melt or not in a ULVZ, for large density increases (see text for details).

possibility includes a thin (~1 km) zone of small but finite rigidity at the top of the outer core; comparing synthetic seismograms for such a "core rigidity zone" (CRZ) with those of a ULVZ that fits the average of the Fiji data (5 km thick, $-\delta V_P$=10%, $-\delta V_S$=30%, $\delta\rho$=0) shows the strong similarity in SP_dKS behavior (Fig. 4). However small the invoked rigidity in this interpretation, the key is that the anomalous zone at the top of the outer core must have a non-zero V_S. We find that values in the range of $V_S \leq$ 1-5 km/s satisfy the Fiji–North America SP_dKS data for thicknesses of 0.5-3.0 km, with densities of 5.8-9.6 Mg/m^3. Tradeoff sheets similar to those of Fig. 2 can be generated, with the results showing that preferred values of thickness are $\leq$ 1 km. For comparison, the velocities and density at the top of the outer core are V_P=8.06 km/s, V_S=0 km/s and ρ=9.60 Mg/m^3 (PREM reference Earth model, *Dziewonski and Anderson,* 1981).

Depending on its chemical make-up, an anomalous zone at the top of the outer core may be more appropriately viewed as a thickened or gradational CMB (i.e., a core-mantle transition zone, CMTZ). For example, a simple linear gradient across a 2 km depth interval between lowermost-mantle and outermost-core velocities of PREM also does well at reproducing the observed seismograms (Fig. 5). Core-reflected PcP waves have been used to suggest that the transition from the mantle to the core occurs over a depth interval less than 1 km [*Kanamori*, 1967; *Vidale and Benz,* 1992]. However, these studies did not sample areas where ULVZ or other anomalous structures have been more recently documented at the base of the mantle or top of the core; it has also been noted that the possible existence of a soft layer at the core–mantle boundary cannot be ruled out [*Kanamori*, 1967]. CMTZ or CRZ models of thickness ~1 km can produce observable waveform distortions (Fig. 6). Changing the thickness yields different separations between the arrivals of SKS and SP_dKS waves, or PcP (or ScP) and precursors (or post-cursors), and can thus be used to model variability in the data. Recently, *Reasoner and Revenaugh* [2000] noted that the coda arrivals of ScP due to CMB boundary layer structure can help to distinguish between a high and low density ULVZ, but high data quality are required. Future studies should consider trade-offs of each of the different data types used in boundary layer modeling.

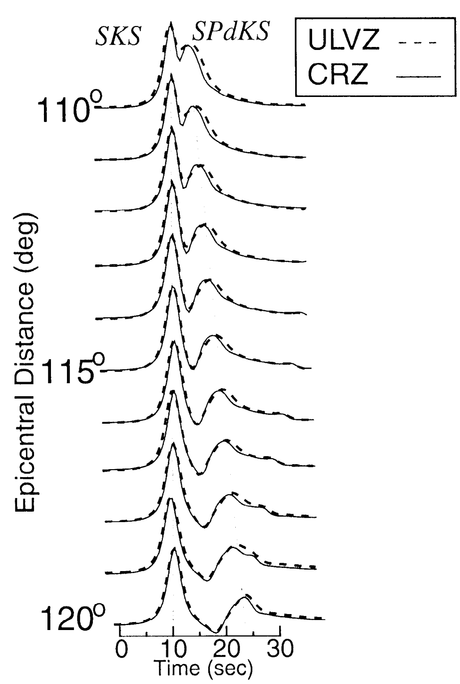

Figure 4. Synthetic seismograms for a ULVZ ($-\delta V_P$=10%, δV_S=30%, $\delta\rho$=0, thickness=5 km) compared with those for a thin zone of finite rigidity at the top of the outer core (V_P=8 km/s, V_S=3 km/s, ρ=9.6 Mg/m^3, thickness=1.5 km).

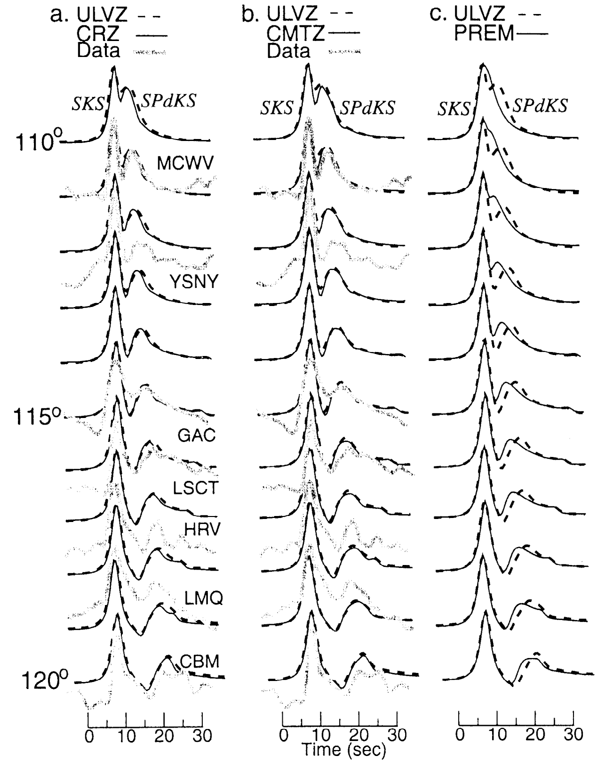

Figure 5. Comparison of Fiji-to-North America data (as in Fig. 1, thick traces) with synthetics for a ULVZ and (a) CRZ model; (b) CMTZ model; and (c) the PREM reference model. Model properties are ULVZ: $-\delta V_P$=10%, $-\delta V_S$=30%, $\delta\rho$=0, thickness=5 km; CRZ: V_P=8 km/s, V_S=3 km/s, ρ=9.6 Mg/m^3, thickness=1 km; CMTZ: thickness=2 km over which properties change from pure mantle to pure core. ULVZ, CRZ and CMTZ waveforms match data well, and are clearly distinguishable from the PREM waveforms.

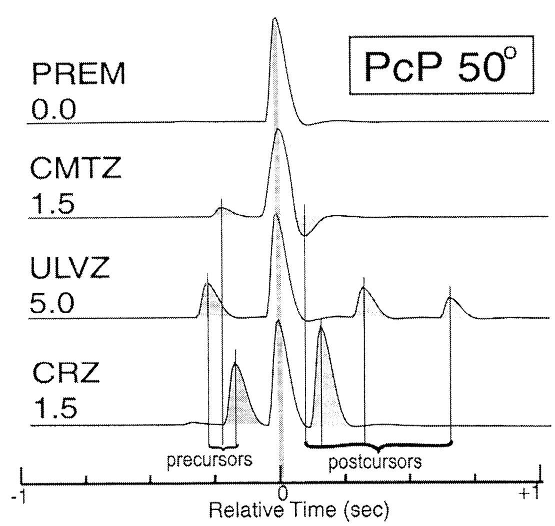

Figure 6. Synthetics for PREM, a CMTZ model, a ULVZ model, and a CRZ model, with layer thickness denoted (in km) beneath model names. Precursors span 0.1 sec. Synthetics are aligned in time and amplitude on PcP.

4. Discussion and Conclusion

The physical interpretation of seismologically anomalous zones at or just below the CMB are necessarily speculative. Crystallization of the outer-core liquid alloy could explain the patchy occurrence of zones having finite rigidity at the top of the core. Chemical reactions between the mantle and core, including "dissolution" of the mantle into the core [*Alder*, 1966; *Knittle and Jeanloz,* 1989, 1991], could play an important role in triggering or modifying anomalies associated with the outermost core or the CMB itself. We note that lateral variations in heat transfer across the CMB could potentially give rise to the observed ULVZ intermittency for any of the proposed structures.

Both partial melting and chemical contamination may be necessary to explain the anomalous data associated with specific patches at (or near) the CMB. Each mechanism has the potential of feeding back on the other, with chemical reactions between the lowermost-mantle rock and the outermost-core liquid alloy helping to sustain partial melting of the lowermost mantle or crystallization of the outermost core (or both). The data thus imply a richness in CMB structural possibilities, including a "fuzziness" or gradational transition between the mantle and core, whether as reduced velocity at the base of the mantle, enhanced rigidity at the top of the core, or a combination of the above. Overall, the observations point to the effects of strong physical and chemical interactions between the Earth's mantle and core.

Acknowledgments. We thank L. Breger, B. Romanowicz, and H. Tkalcic for fruitful discussions and comments. The manuscript improved from thoughtful reviews by B. Buffett, C. Reasoner, J. Revenaugh, and an anonymous reviewer. Work partially supported by NSF grant EAR-9905710.

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(Received January 10, 2000; revised April 14, 2000; accepted June 23, 2000.)