U

ULVZ, ULTRA-LOW VELOCITY ZONE

Nearly half way to Earth's center, the boundary between the solid silicate rock mantle and the liquid iron-alloy outer core was long thought to be a sharp discontinuity between the two vastly different regimes. Recently, detailed seismological analyses have depicted the core–mantle boundary (CMB) as being far from simple, and in fact shows evidence for an additional thin veneer of anomalous properties in certain geographical regions. Imaged as thin as a couple of km, and up to 50-km thick, these unique zones are characterized by strong reductions in the speeds of seismic waves relative to the overlying mantle. These areas have thus been dubbed "ultra-low velocity zones" (ULVZs).

Seismic probes

Seismology remains the most direct remote sensing tool for deciphering the subtleties of Earth's inaccessible deep interior. This is most commonly accomplished through the use of elastic energy that propagates away from earthquakes, traveling through the entire interior of the planet; some energy propagates continuously through the Earth, some reflects from local or global boundaries between contrastingly different materials, and some of it, in special cases, diffracts along boundaries between strongly contrasting media. Each of these types has provided evidence for extremely sluggish patches at the CMB.

Four of the most commonly utilized seismic probes (or "phases") to date are *SPdKS* referenced to *SKS*, and precursors (seismic energy that just slightly precedes a later more dominant phase) to the waves *PcP*, *ScP*, or *PKP* (Figure U1). Over the past decade a variety of research groups have documented anomalies in these arrivals and attributed them to CMB structure (see, e.g., Garnero *et al*., 1998). *ScP* is a seismic phase that departs from the earthquake as an *S* wave, and upon reflection at the CMB, converts to a *P* wave (Figure U1a). If a low velocity boundary layer is present at the CMB, several additional arrivals are possible (Figure U1a, second panel). The relative timing and amplitude of these arrivals is apparent in a computer generated "synthetic" seismogram 60° in arc away from a 500-km deep hypothetical earthquake (third panel). If the top of the layer is diffuse, then these arrivals diminish in amplitude, which remains an active direction for current research.

Figure U1b shows *PcP*, which also contains pre- and postcursors, analogously to *ScP*, as well as some of the additional arrival geometries, and a synthetic seismogram showing the additional arrivals. One challenge in data analyses is to identify the later arrivals, since they are commonly obscured by the coda of the main *PcP* phase, i.e., additional arrivals due to (for example) reverberations in Earth's crust due to the *PcP* wave.

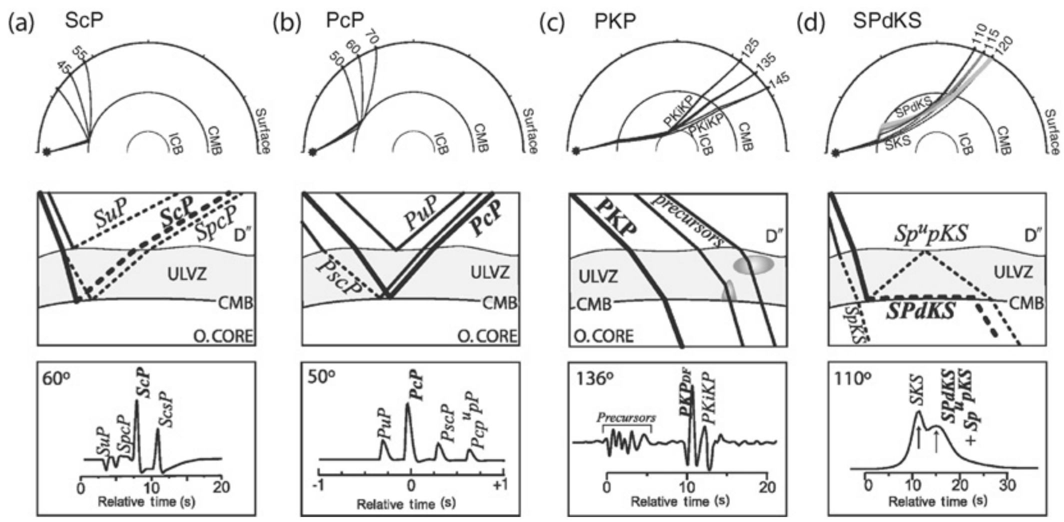

Figure U1 Ray paths, seismic arrivals due to a ULVZ, and synthetic seismograms for (a) *ScP*, (b) *PcP*, (c) *PKP*, and (d) *SPdKS*. Synthetic seismogram predictions of (a) and (c) are from Garnero and Vidale (1999) and Wen and Helmberger (1998), respectively.

Waves that travel into the Earth's core can contain important information about anomalous properties at the CMB, which they traverse at least twice. The phase *PKP* has been used to detect CMB structures that scatter energy resulting in precursory arrivals to *PKP*. Figure U1c shows *PKP* paths, along with an associated reference arrival *PKiKP* that reflects from the inner core boundary. Anomalous topography to the ULVZ or inclusions of low velocity material can give rise to precursory arrivals, as shown in the theoretical predictions in the bottom panel.

Another important probe of the CMB is an *S* wave that encounters the CMB at a critical angle to produce a *P* wave that diffracts along the CMB (*Pd*), then continues into the core as a *P* wave, then back through the mantle as an *S* wave (Figure U1d). This phase, *SPdKS*, has short segments of *P* wave diffraction at the core entry and exit locations. Additional internal reflections within the layer are also emerging as important (e.g., *SPuPKS*). Certainly other possible seismic probes of ULVZ structure are possible, as long as seismic energy either refracts, diffracts, or reflects at the CMB.

An important next step in ULVZ research will be to find geographical regions that permit analysis of more than one particular seismic phase, since different waves are sensitive to different ULVZ structural components. For example, the precursor analyses (Figure U1a–c) utilize short period energy, which is particularly sensitive to sharp contrasts in properties, and not able to well-resolve gradational changes in properties. *SPdKS*, on the other hand, is less sensitive to such contrasts, but very sensitive to the velocity structure within the layer, particularly at distances where the *Pd* segment in *SPdKS* is short.

Ultra-low velocity boundary layer possibilities

The seismic phases introduced in Figure U1 have played a critical role in revealing several possibilities for transitional structure between the core and mantle. Three main possibilities are highlighted here: a layer on the mantle side of the CMB (which is most commonly referred to as ULVZ), a layer on the core-side of the CMB (essentially a core-rigidity zone, CRZ), and some thickness over which the mantle changes into the core (hereafter denoted as a core–mantle transition zone, CMTZ) (Figure U2). It is important to recognize these as end-member models, and that any combination of these is equally possible.

Mantle ultra-low velocity zone

ULVZ thickness has been imaged between 5 and 50km, with strong lateral variations. The most commonly explored model parameters are those compatible with partial melt of the lowermost mantle, which results in a three times larger reduction in shear velocity (e.g., 30%) than that for compressional waves. Density increases are also possible (Figure U2a).

Core-rigidity zone

If large density increases and shear velocity decreases are considered in ULVZ modeling, one must allow for the possibility of the layer residing on the core-side of the CMB (Figure U2b). The liquid outer core of the Earth is predominantly iron, along with a minor constituency of some lighter element(s). As the Earth cools, the solid inner core of the Earth grows, releasing the lighter elements into the outer core, which may result in "underplating" of the CMB in a sedimentation process (see Buffett *et al*., 2000). Thus, isolated regions of nonzero rigidity may exist beneath positive topography, or, "hills" on the CMB, where such sediments can accumulate and concentrate (up to a couple km thick; Rost and Revenaugh, 2001). If electrically conductive, the CRZ may affect Earth's magnetic field, nutations, and possibly even magnetic field reversal paths.

Core–mantle transition zone

Finally, we consider the possibility of a transitional zone between the mantle and core over some finite thickness (Figure U2c). Chemical reactions between the silicate rock mantle and liquid iron-alloy outer core (see Knittle and Jeanloz, 1989) can result in a thin mixing zone—an effective blurring of the CMB. The CMTZ can appropriately cause precursors to the short period waves (Figure U1a–c) as well as delay the SPdKS relative to SKS (Figure U1d; Garnero and Jeanloz, 1998).

ULVZ geographic distribution

To gain insight into the possible origin of ultra-low velocity layering at the CMB, it is instructive to compare results to other phenomena, such as gross properties of the deep mantle as revealed by shear wave tomography. Figure U3 compares the strongest variations in shear wave velocity with ULVZ distributions. There is suggestion of a connection between ULVZ and low seismic wave speeds (Figure U3a,b). This ULVZ distribution also correlates strongly with hot spot volcanism at Earth's surface (Williams *et al*., 1998). However, an examination of a larger data set of higher quality broadband data reveals shorter scale variations, with some CMB patches showing evidence for both support and lack of an anomalous layer. Figure U3c summarizes ULVZ likelihood using broadband digital *SPdKS* data. The correlation with large-scale lower mantle shear velocity is more difficult to assess. Greater geographical coverage in future studies will allow more confidence in such comparisons. A main limitation in achieving greater spatial coverage is uneven earthquake and seismometer distribution on the globe, limiting where the deep interior can be probed.

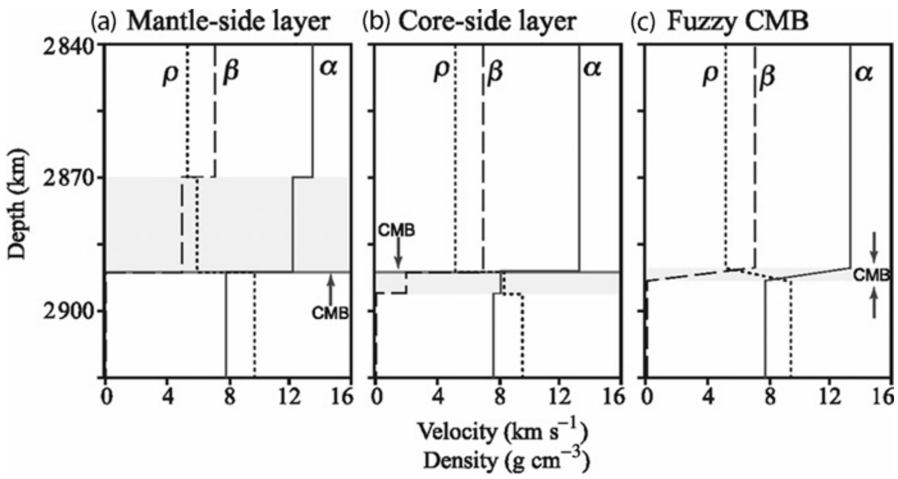

Figure U2 P-wave (α) and S-wave (β) velocity and density (ρ) versus depth for ultra-low velocity boundary layering (shaded regions) on (a) the mantle-side of the core–mantle boundary (CMB) (a ULVZ) (b) the core-side of the CMB (a CRZ), and (c) a finite thickness transition between the mantle and core (CMTZ).

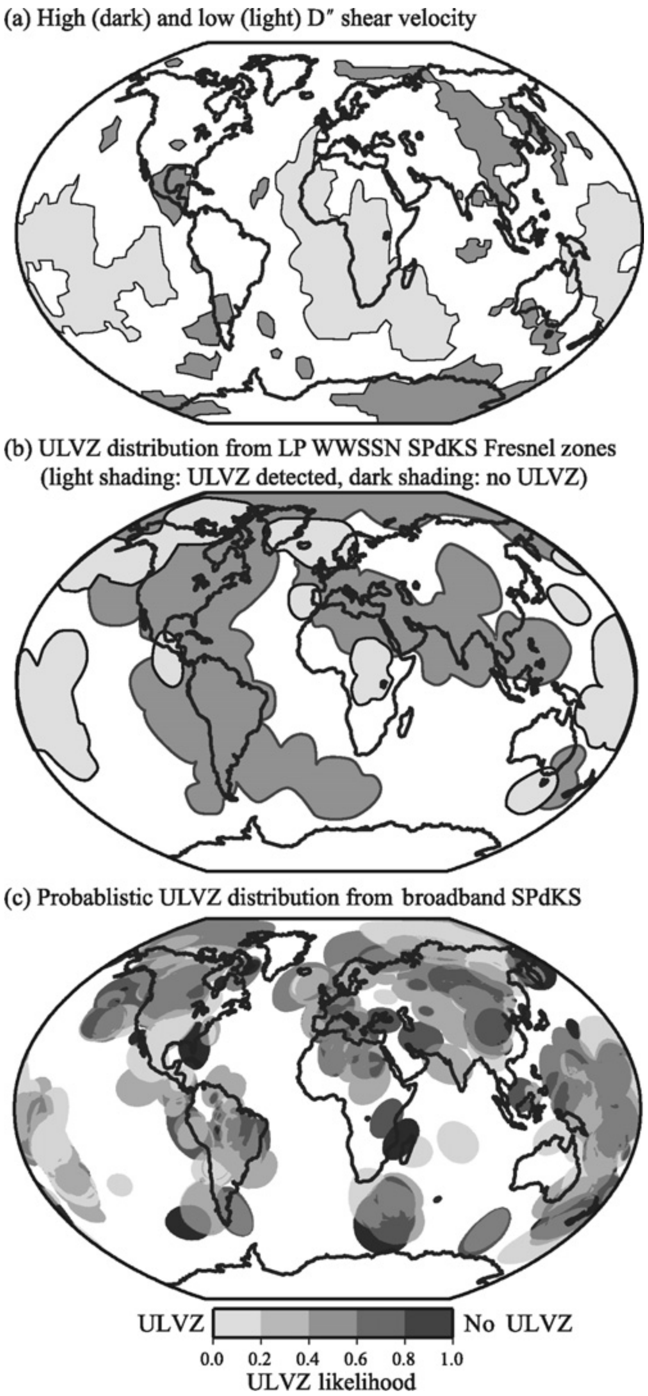

Figure U3 (a) Shear velocity distribution in the lowermost 250km of the mantle from the model of Grand (2002). Light shaded areas have velocities equal to or lower than −1% relative to the global average, dark areas are at or great than +1%. (b) Fresnel zones of *SPdKS* sampling at the CMB from long period analog data. Light shading is for suggested ULVZ presence; dark shading for ULVZ absence, and no shading represents no data sampling. (c) Same as (b), except using modern broadband digital data, and shading represents the likelihood of ULVZ presence. For each 1°×1° section of the CMB with data coverage, the following ratio is constructed and plotted: (# of records requiring an ultra-low velocity layer)/(total # of records for that cell). Thus, a value of 1 indicates all data that traversed that cell are anomalous; a value of 0 represents the case where no data sampling a particular region are anomalous (after Thorne and Garnero, 2004).

Discussion and summary

While confident correlations between ULVZ layering and bulk mantle properties may be premature at present, the existence of the layer is clear, from a variety of studies and methods. While not constrained, it is instructive to briefly consider possible scenarios relating CMB structure to the thermal, chemical, and dynamical environment. Figure U4 displays a multitude of possibilities beneath upwelling and downwelling mantle regimes. The point here is to recognize the variety of structures and their scale lengths that are possible, yet unresolved at present, and hence future work should seek to sharpen our focusing ability for such possibilities.

Beneath upwelling regions, possibilities include (but certainly are not limited to) (a) a combination of ULVZ, CMTZ, and CRZ structures in the hottest lowermost mantle regions; (b) convection within a partially molten ULVZ which can sweep chemical heterogeneity into localized piles within the ULVZ; (c) large- and fine scale CMB (as well as ULVZ) topography, resulting in (d) multiple scale CRZs of variable strength; (e) some ULVZ melt entrainment into overlying convection currents, which may result in (f) mantle plume genesis, and (g) aligned melt pockets from strong boundary layer shear flow, yielding seismic anisotropy; and (h) chemical mixing between the ULVZ and outer core (or CRZ) material, giving rise to local (or widespread) CMB blurring, including chemical coupling (or interactions).

Beneath downwelling regions, similar phenomena exist, but perhaps suppressed in the vertical dimension (a) spatially organized ULVZ to the front of downwelling motions, where plume instabilities (thus local warmer zones) have been shown to exist (Tan *et al*., 2002); (b) a thin (undetectable?) ULVZ throughout region; (c) small- and large-scale CMB topography, which may provide localized basins or wells for material with density intermediate to that of the mantle and core; (d) possible chemical contamination from melt from either CMB chemical reaction product entrainment or ponding of former oceanic crust; and (e) anisotropy due to high strains resulting from overlying subduction stresses (McNamara *et al*., 2002). While provocative, Figure U4 depicts the likely scenario of CMB topography that is intimately coupled to ULVZ, CMTZ, and CRZ chemistry and dynamics. Furthermore, these structures probably play an important role with electromagnetic, gravitational, thermal, and topographic coupling between the mantle and core.

Future analyses should incorporate more realistic 3D wave propagation tools for predictions to compare to data (see, e.g., Helmberger *et al*., 1998). Analyses that utilize more that one of the wave types presented in Figure U1 for the same patch of the CMB will also greatly reduce uncertainties.

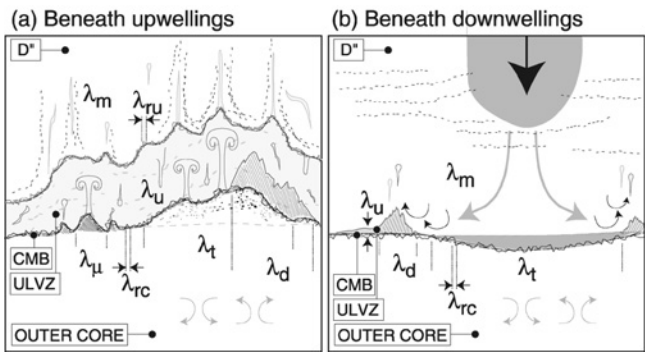

Figure U4 Possible CMB scenarios beneath regions of (a) upwelling, and (b) downwelling (see text for details). Significant (or total) uncertainty exists for many wavelengths of interest, which include: scale-length over which ULVZ phenomena affects the lowermost mantle (λ_m), scale lengths of roughness of the top of the ULVZ (λ_{ru}), ULVZ thickness distribution (λ_u), dimension of isolated core-rigidity zones (λ_μ), scale of roughness of the CMB, including the thickness of transition from pure core-to-mantle (λ_{rc}), lateral and vertical scale of long wavelength CMB topography, and hence possible anomalous zones contained within the topographic depressions/elevations (λ_t), and isolated thermochemical domes, scatterers, or anomalous shapes within the ULVZ (λ_d).

Lastly, it is clear that ULVZ structure is an intimate part of the core–mantle transition, and likely reflects core processes that may be related to the geodynamo. For example, if the ULVZ is enriched in iron from the core, it may affect geomagnetic reversal path geometries, which to the first order appear anticorrelated with ULVZ distributions (Garnero *et al*., 1998). Certainly, uneven geographic distribution of patches of partially molten and/or chemically unique ULVZ material can result in variability in core heat flow that may affect core fluid motions, possibly relating to Earth's magnetic field generation and variability.

E. Garnero and M. Thorne

Bibliography

Buffett, B.A., Garnero, E.J., and Jeanloz, R., 2000. Sediments at the top of the Earth's core. *Science*, **290**: 1338–1342.

Garnero, E.J., and Jeanloz, R., 1998. Earth's enigmatic interface. *Science*, **289**: 70–71.

Garnero, E.J., and Vidale, J., 1999. ScP; a probe of ultralow-velocity zones at the base of the mantle. *Geophysical Research Letters*, **26**: 377–380.

Garnero, E.J., Revenaugh, J.S., Williams, Q., Lay, T., and Kellogg, L.H., 1998. Ultralow velocity zone at the core–mantle boundary. In Gurnis, M., Wysession, M., Knittle, E., Buffet, B., (eds.) *The Core–Mantle Boundary.* Washington, DC: American Geophysical Union, pp. 319–334.

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

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*, **396**: 251–255.

Knittle, E., and Jeanloz, R., 1989. Simulating the core–mantle boundary: an experimental study of high-pressure reactions between silicates and liquid iron. *Geophysical Research Letters*, **16**: 609–612.

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*, **416**: 310–314.

Rost, S., and Revenaugh, J., 2001. Seismic detection of rigid zones at the top of the core. *Science*, **294**: 1911–1914.

Tan, E., Gurnis, M., and Han, L., 2002. Slabs in the lower mantle and their modulation of plume formation. *Geochemistry, Geophysics, Geosystems*, **3**(11): 1067 (doi: 10.1029/2001GC000238).

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

Wen, L., and Helmberger, D.V., 1998. Ultra-low velocity zones near the core–mantle boundary from broadband PKP precursors. *Science*, **279**: 1701–1703.

Williams, Q., Revenaugh, J.S., and Garnero, E.J., 1998. A correlation between ultra-low basal velocities in the mantle and hot spots. *Science*, **281**: 546–549.

Cross-references

Core Composition
Core Properties, Physical
Core, Boundary Layers
Core–Mantle Boundary
Core–Mantle Boundary Topography, Implications for Dynamics
Core–Mantle Boundary Topography, Seismology
Core–Mantle Coupling, Electromagnetic
Core–Mantle Coupling, Thermal
Core–Mantle Coupling, Topographic
Core–Mantle Boundary, Heat Flow Across
D″ as a Boundary Layer
D″, Anisotropy
D″, Composition
D″, Seismic Properties
Earth Structure, Major Divisions
Geodynamo, Numerical Simulations
Seismic Phases