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MANTEL D\textsuperscript{''} LAYER

Thorne Lay

University of California, Santa Cruz, CA, USA

Definition and introduction

Earth’s lower mantle extends from the base of the transition zone (commonly assigned a depth of 660 km, corresponding to the average depth of a global seismic velocity discontinuity) to the core-mantle boundary (CMB) at a depth of \( \sim 2,900 \) km below the surface. This thick layer of rock comprised of silicate and oxide minerals has gradual increases with depth of P- and S-wave seismic velocities and density that are generally consistent with adiabatic self-compression of a uniform composition material over most of the depth range (see Structure of Earth’s Lower Mantle). Large-scale lateral heterogeneities in the seismic velocities of about \( \pm 1\% \) are apparent in the central lower mantle, and these likely involve thermal and chemical signatures of upwellings and downwellings in the slowly convecting deep mantle system (see Mantle Convection). The deepest few hundred kilometers of the lower mantle have generally reduced seismic velocity gradients, localized seismic velocity discontinuities, and strong large-scale seismic velocity heterogeneities of \( \pm 2-4\% \). This portion of the lower mantle is called the D\textsuperscript{’} layer (or, more commonly, the D\textsuperscript{’} region, because the onset of anomalous properties varies significantly in height above the CMB from place to place) in recognition of its distinctive properties relative to the shallow lower mantle (D\textsuperscript{’} layer). Localized regions of extreme (10–30\%) seismic velocity reductions in thin layers or lumps only tens of kilometers thick are found at the base of D\textsuperscript{’}. The structural heterogeneities in the D\textsuperscript{’} region are usually interpreted as manifestations of complex thermal and chemical boundary layers at the CMB, to some extent mirroring the structural heterogeneities found in the near-surface lithospheric boundary layers. The structure and dynamics of the D\textsuperscript{’} region are believed to be of fundamental importance to the mantle and core dynamical systems, prompting many seismological, geodynamical, and mineral physics investigations of D\textsuperscript{’} properties.

The D\textsuperscript{’} region may have distinct bulk composition from the rest of the lower mantle, involving residues from deep mantle melting, core formation, chemical reactions between the core and mantle, or dynamical segregation of materials over time, but this possibility has to be assessed in the context of expected behavior of major lower-mantle minerals for the extreme pressure-temperature (P-T) conditions near the CMB. The primary minerals in the lower mantle are thought to be \((\text{Mg,Fe})_2\text{SiO}_4\) perovskite, \((\text{Mg,Fe})_2\text{SiO}_4\) ferropericlase, and smaller amounts of \(\text{CaSiO}_3\) perovskite and high-pressure forms of \(\text{SiO}_2\) (see Structure of Earth’s Lower Mantle). The relative amount of Mg versus Fe, given by \(x\), is \(\sim 0.9\), but the properties of the minor Fe component are being intensely investigated because transitions from high-spin to low-spin in \(\text{Fe}^{3+}\) and \(\text{Fe}^{2+}\) are expected in lower mantle perovskite and ferropericlase as pressure increases, with strong effects on chemical and transport properties of the material in the deep mantle. Some Al may substitute in both the Mg and Si sites in the Mg-perovskite. Mg-perovskite comprises as much as 70\% of the lower mantle, making it the most abundant mineral in the Earth. A phase change in Mg-perovskite, discovered in 2004, occurs under P-T conditions existing a few hundred kilometers above the CMB, likely giving rise to some of the complexities of the D\textsuperscript{’} region (Hirose and Lay, 2008). Mineralogical complexity of D\textsuperscript{’} is expected to be enhanced relative to the bulk of the lower mantle due to proximity to huge contrasts in composition and physical properties across the CMB.
The CMB separates the solid silicate- and oxide-mineral mantle from the molten metallic-alloy outer core. The density increases from about 5,500 kg/m³ to 9,900 km/m across the CMB, and the viscosity decreases by many orders of magnitude. These contrasts maintain a very sharp boundary and result in thermal and chemical boundary layers in both D″ and the outermost core, although any core structures may be very thin and hard to detect (see Structure of Earth’s Core). With any mass flux across the CMB being constrained to involve chemical diffusion, heat transports across the CMB by conduction from the hot core into the lower-temperature mantle. The temperature drop across the resulting CMB thermal boundary layer is estimated to be in the range 1,000–2,000°C, and there is a heat flow of 5–15 TW across the boundary (the heat flow through Earth’s surface is ~46 TW) (Lay et al., 2008). Over time, relatively dense materials in the mantle (for example, any basaltic basaltic in subducted slabs that penetrate into the lower mantle) are likely to have concentrated in D″, while light dross, expelled from the core may have accumulated on the underside of the CMB. Thermo-mechanical and electromagnetic interactions across the CMB couple the mantle and core dynamical systems, and this influences the geodynamo (see Core-Mantle Interaction). The D″ region is relatively accessible to seismic imaging, and its inferred structural and dynamical properties are discussed here. Tronnes (2009), Garnero and McNamara (2008), Lay (2007), and many papers in Hirose et al. (2007) provide technical reviews of ongoing research topics and conceptual models for structures and processes occurring in D″.

Seismic velocity models for D″

Seismology provides the highest resolution of D″ elastic material properties because it is possible to decipher seismic wave interactions with the lowest mantle and CMB in recordings of ground shaking at seismic stations around the world. Seismic wave observations can resolve D″ region P- and S-wave velocities, reflections from sharp velocity jumps, shear-wave splitting caused by anisotropy of the elastic structure, and scattering properties. One-dimensional (1D) depth-varying seismic velocity models, such as the Preliminary Reference Earth Model (PREM) of Dziewonski and Anderson (1981), usually have reduced velocity gradients in the deepest ~150 km of the mantle, representing the global departure of D″ velocity structure from that of the overlying lower mantle. Efforts were initially made to interpret the low (or even negative) velocity gradients in such laterally averaged models of D″ structure as the result of a superadiabatic temperature increase across the CMB thermal boundary layer; strong temperature increases are required to account for seismic velocity reductions due to the low thermal expansion coefficient of deep mantle rock under high pressures. However, it is now clear that there is no meaningful “average” 1D structure for the D″ region useful for a robust interpretation of the boundary layer. It is more useful to discuss the seismic properties of D″ by emphasizing the lateral variations in structure, as is also the case for the lithosphere.

Seismic tomography has been applied to develop three-dimensional (3D) seismic velocity models for the entire mantle for over 30 years. This method extracts 3D P-wave and S-wave velocity fluctuations relative to 1D reference models by inversion of massive data sets with crossing ray paths for which seismic wave travel times are measured. 3D velocity inversions indicate that seismic velocity heterogeneity in the mid-lower mantle is relatively weak, but that in the lowermost 300–500 km of the mantle heterogeneity increases with depth, becoming stronger in D″ than anywhere else in the Earth except for the uppermost mantle where major thermal, chemical and partially molten heterogeneities are known to exist.

An unanticipated aspect of the D″ seismic velocity heterogeneity revealed by seismic tomography is that it is dominated by large-scale patterns, with huge continuous volumes of high or low-seismic-velocity material having scale-lengths of hundreds to thousands of kilometers. This predominance of large-scale variations is observed in both P-wave and S-wave velocities, with relatively high-velocity regions of D″ underlying the circum-Pacific margins and two nearly antipodal regions of pronounced low S-wave velocity beneath the southern central Pacific and southern Africa/southern Atlantic/southern Indian Ocean (Figure 1a). High-seismic-velocity regions are likely to have lower temperature than low-seismic-velocity regions, although chemical differences and phase changes may contribute to the variations. Recent global tomographic models have ±4% S-wave velocity variations in D″, two or three times stronger than those found in the mid-lower mantle, and comparable to the ±5–8% variations at depths near 150 km in the upper mantle. While mid-mantle variations tend to have more spatially concentrated heterogeneities, there is a significant degree of radial continuity of high- and low-velocity anomaly patterns throughout the lower mantle, possibly linking subduction zones at the surface to high-velocity regions in D″ and hot-spot locations at the surface to low-velocity regions in D″ (Garnero and McNamara, 2008).

P-wave velocity variations in current tomographic models have ±1.0–1.5% fluctuations, with low-velocity areas beneath the southern Pacific and south Atlantic/Africa and high velocities under eastern Eurasia. There is not as strong of an increase in P-wave velocity heterogeneity in D″ relative to that in the overlying mantle as there is for S-wave velocity, which can be partially attributed to the expected greater sensitivity of S-wave velocity to temperature variations in a thermal boundary layer. There is a large-scale spatial correlation between S- and P-wave velocity patterns, as expected for temperature-induced variations, but in some regions, such as beneath the northern Pacific, this correlation breaks down. In other regions, such as beneath the central Pacific, the S-wave variations are much stronger than the P-wave variations even though both have the same sign. The decorrelation of the seismic
velocities and the variation in their relative strengths provide strong evidence that thermal variations alone cannot explain the large-scale patterns of seismic velocity heterogeneity; so there is likely to be chemical heterogeneity present in D" (Trampert et al., 2004). It is important to recognize that tomography patterns are relative to the global average velocities at D" depths, and that these averages do not necessarily define “normal” mantle structure. This results in uncertainty in interpretations of the velocity fluctuations (for example, high velocity regions may be anomalously low temperature, perhaps due to cool downwellings that have disrupted an overall hot boundary layer, or low-velocity regions may be anomalously hot regions, perhaps partially melted, within a chemically distinct, high velocity layer). Resolution of finer scale seismic properties in D" is pursued in order to overcome this ambiguity in interpreting global seismic tomography images.

Seismic velocity discontinuities in D"

Rapid P-wave and S-wave velocity increases and/or decreases are observed several hundred kilometers above the CMB in many regions (Lay and Garnero, 2007), and are sometimes used to define the top of D". The most prominent structure is a rapid shear velocity increase of 1.5–3% 150–350 km above the CMB found over intradie-scale (500–1,000 km) regions beneath circum-Pacific margins and some other locations (Figure 1a). The increase in velocity may be distributed over a few tens of kilometers or it may be very abrupt (a “discontinuity”) (Lay, 2008), and in some regions it can vary in depth by as much as 100 km over lateral scales of just 200 km. The velocity increase is required to account for observed S-wave reflections that arrive before reflections from the CMB. Similar structures have been found in localized regions for P-waves, usually with a smaller velocity increase of 0.5–1.0%, but in some regions there is a P-wave velocity decrease at the same depths as an S-wave increase (Hutko et al., 2008). Lay and Garnero (2007) review many observations and models for this D" seismic velocity discontinuity.

The D" S-wave velocity discontinuity is commonly observed in regions with large volumes of high S-wave velocity material in D", indicating that it is associated with relatively low temperature environments. An abrupt increase in velocity with depth is not expected for a thermal boundary layer structure, so most interpretations of this correlation invoke the notion of localized ponding of cool subducted lithospheric slabs that have sunk to the lowermost mantle, retaining enough thermal and chemical anomaly to account for the high seismic velocity. However, it is not clear that slab thermal and compositional anomalies can account for a sharp reflecting structure, so additional presence of a phase change may be required. Alternatively, chemically distinct high velocity material may be present in these regions, perhaps involving ancient accumulated material concentrated during core formation or segregated oceanic crustal materials that have accumulated over Earth history. Observations of an S-wave velocity increase beneath the central Pacific, a relatively low velocity region far from any historical subduction zone, complicates any attempt to interpret the velocity discontinuity solely as the result of recent slabs thermal anomalies (Lay and Garnero, 2007).

Post-perovskite in D"

The major seismic velocity discontinuities in the transition zone are generally attributed to phase changes in upper mantle minerals that cause abrupt changes in density and elastic wave velocities. The experimental discovery of a phase transition in MgSiO₃ perovskite (Murakami et al., 2004) for P-T conditions near the top of D” may provide a corresponding explanation for the D” S-wave velocity discontinuity. The high-pressure polymorph is called post-perovskite, and laboratory and theoretical predictions of its properties indicate that it should have 1–2% higher S-wave velocity, little, or no change in P-wave velocity, and 1–1.5% higher density than perovskite, which can account for some of the seismological complexities of D” (Hirose et al., 2007). Presence of Fe and Al in the perovskite cause the phase transition to occur over a pressure range rather than at a single pressure for a given temperature, and this may be difficult to reconcile with an efficient seismic wave reflector. The perovskite-to-post-perovskite transition occurs at lower pressure for lower temperatures, thus lateral temperature variations in a thermal boundary layer are expected to modulate the depth of the transition. If the phase transition occurs in a relatively cool region of accumulated downwell slab material, the discontinuity should be higher above the CMB than in warmer areas of D” with the same composition. Some calculations indicate that the pressure of the transition may decrease if Fe is present in the perovskite, thus chemical heterogeneity could also modulate the depth of the phase transition. The P-T behavior of the post-perovskite phase change tends to enhance thermal instabilities within the thermal boundary layer, but its thermal transport properties are still uncertain due to the possibility of Fe high-spin to low-spin transition and the lack of constraint on Fe partitioning coefficients between post-perovskite and ferropericlase.

One of the most important attributes of the phase transition is that it can provide an absolute temperature tie-point for D” if an observed S-wave reflector at a specific depth (hence, pressure) is correctly attributed to the phase change and if the P-T-X behavior (where X indicates precise mineralogical composition) of the phase change is experimentally and theoretically constrained. This is important because estimates of temperature structure in the lowermost mantle and outermost core are largely based on extrapolations over tremendous depth ranges.
the iron alloy solidus at the 5,150-km deep inner core-
outer core boundary.

Laboratory measurements indicate that the temperature at a depth of about 2,600 km is close to 2,500 K, if the D’
 discontinuity is caused by transition to post-perovskite. With an estimated outermost core temperature of 3,500–
4,000 K, this favors a 1,000–1,500’ increase in tempera-
ture across the D’’ thermal boundary layer. Such a strong
temperature increase could cause a reversion from post-
perovskite to perovskite to take place in the hottest region
right above the CMB, and some evidence for such
a second crossing of the phase boundary has been inferred
from seismic observations of a S-wave velocity decrease
50–100 km above the CMB (Figure 1a; Lay et al., 2006;
van der Hilst et al., 2007). The effects of the phase transi-
tion on seismic velocities must be considered when infer-
rting lateral velocity structure in D’’ from seismic
velocity variations, given that the volume of the high
S-wave velocity post-perovskite material should vary lat-
erally in either a depth-modulated layer or a “lens,”
depending on stability of post-perovskite right at the
CMB.

Large low shear velocity provinces in D’’
The two large antipodal regions with low S-wave velocity
appear to be chemically distinct regions of D’’ (Figure 1a).
The margins of these large low shear velocity provinces
(LLSVPs) have abrupt steep-walled lateral gradients, over
scales of tens of kilometers, which indicates a chemical
change relative to surrounding D’’ material rather than just
a thermal change. The region beneath the southern
Atlantic and Africa has been modeled as having margins
with an abrupt −1 to −3% S-wave velocity decrease
250–300 km above the CMB (shallowing to ~300 km
above the CMB under Africa), with average velocities in
D’ that are 3–5% lower than for PREM (e.g., Wang and
Wen, 2006). The sub-Pacific LLSVP has comparable
velocity contrasts and varying vertical extent and may
be two separate mounds of material that extend upward
into the central lower mantle. P-wave velocity tends to
be slightly low in the LLSVPs, but less than what would
be expected if the S-wave velocity reductions were
entirely caused by high temperatures. Thus, there is an
anomalously high incompressibility in the LLSVPs,
which also favors distinct chemistry. While limited in res-
solution, free oscillation measurements suggest that the
LLSVPs are relatively high density, adding to the evi-
dence for chemical inhomogeneity, and suggesting that
these are not buoyant ‘superplumes’ as some researchers
have suggested. Internal structure of LLSVPs has been
detected in the form of localized velocity discontinuities
(Figure 1a) and the presence of underlying ultra-low-
velocity zones (see below). The velocity discontinuities
may represent chemical heterogeneity or possibly post-
perovskite phase transition in material with distinct Fe
and Al content from surrounding high seismic velocity
areas of D’’.

The current position of the LLSVPs can be attributed to
accumulation of chemically distinct, relatively dense
material in D’’ that has been displaced away from
circum-Pacific areas of downwelling slab materials over
the past several hundred million years (Garnere and
McNamara, 2008). Thermal calculations indicate dense
chemical piles in a convecting mantle which will be rela-
tively hot as a result of inefficient heat loss, so LLSVPs
would likely have combined effects of high incompre-
sibility, high temperature, and high density. This predicts
complex dynamical behavior, but the presence of the
structures in D’’ at this point in Earth’s evolution suggests
that the features are long-lived and are either remnants of
much larger chemical anomalies that have slowly been
entrained by mantle flow or they are being regenerated
by ongoing chemical differentiation. Aggregation of
basaltic (ocean crust) components of subducted slabs is
one possible mechanism for accumulation of chemically
distinct material that may be sustaining the LLSVPs. The
total volume of LLSVP material is several percent of the
mantle, so these are significant chemical reservoirs. The
possibility that the LLSVPs have been close to their pre-
sent locations for hundreds of millions of years is
supported by the fact that reconstructed emplacement
locations of many Large Igneous Provinces (LIPs) overlap
margins of the LLSVPs (Torsvik et al., 2006). If plume
upwellings rise from the lateral margins of the dense piles,
as suggested by numerous dynamical models, this associa-
tion may be understood as a first order impact of D’’
structure on geological processes at Earth’s surface.

Ultra-low velocity zones in D’’
Thin layers or mounds of material with very strong seismic
velocity reductions have been detected in D’’ just
above the CMB (Figure 1b), and these are called ultra-
low velocity zones (ULVZs). P- and S-wave velocity
models for ULVZ may have a thin layer or mound of 10–40 km thick and from hundreds to thousands of kilo-
meters across with P-wave velocity reductions of ~4 to
~10% and S-wave velocity reductions of ~8 to ~30% (Thorne and Garnere, 2004). These structures are com-
monly found near the margins of LLSVPs (Figure 1a),
but also occur in localized regions elsewhere. They are
detected in seismic waves that reflect from or graze along
the CMB.

The magnitude of the velocity reductions in the ULVZs
and the factor of 2–3 ratio of S-wave velocity/P-wave
velocity decrement require either the presence of a melt
component or very strong chemical contrast. The tempera-
ture in the D’’ thermal boundary layer will reach a peak
right at the CMB (which is nearly isothermal due to the
rapid convective flow occurring in the core); so ULVZs
are intrinsically the hottest regions in the mantle. How-
ever, they are not globally detectable (a very thin
layer < ~1 km could be present everywhere without being
resolved by seismic data); so a combination of partial
melting and chemical heterogeneity is implied by the
patchy nature of the thicker regions of ULVZ. Seismic data indicate that the ULVZ material may be ~10% denser than surrounding D" material, favoring high Fe content, which would contribute to the strong seismic wave velocity reductions. ULVZ affiliation with LLSVP margins may be associated with thermal convection in the LLSVPs, along with interactions with flow in the surrounding mantle (Garnero and McNamara, 2008). It is not yet clear how to account for ULVZ chemical evolution, but one possibility is that they are the residue of a much more extensive lower mantle magma ocean which has largely solidified (Labrosse et al., 2007).

Seismic velocity anisotropy in D"

The seismic velocity structure in D" is more anisotropic than the shallower lower mantle, with seismic velocities being dependent on the direction of propagation and the polarization of ground shaking. This results in shear-wave splitting, involving an S-wave separating into two components with orthogonal polarization, one traveling slightly faster than the other while in the D" region. By measuring the polarizations and travel time difference between the fast and slow S-waves, it is possible to determine the anisotropic characteristics of the medium. For most S-wave phases with ray paths grazing horizontally through the D" region, the data can be explained by models in which horizontally polarized (SH) vibrations travel with 1–3% higher velocities (Vsh) than vertically polarized (SV) vibrations (Figure 1c). This behavior is consistent with the medium having vertical transverse isotropy (VTI), which can result from hexagonally symmetric minerals with vertically oriented symmetry axes or from stacks of thin horizontal layers with periodic velocity fluctuations. The regions with the best documented cases for strong VTI in D" tend to have higher than average S-wave velocities and strong D" discontinuities (Figure 1c). There are observations favoring slightly tilted (non-vertical) transverse isotropy (Maupin et al., 2005), which results in weak coupling of the SH and SV signals (the fast wave is still close to the SH polarizations), as well as limited regions where SV signals are found to propagate with higher velocities (Vsv) than SH signals (such as in the central Pacific LLSVP, Figure 1c).

Anisotropy in D" is likely to be caused by either lattice-preferred orientation (LPO) or shape-preferred orientation (SPO). LPO can arise when minerals systematically orient preferred orientation (LPO) or shape-preferred orientation signals (such as in the central Pacific LLSVP, Figure 1c). There are observations favoring higher than average S-wave velocities and strong D" velocity fluctuations. The regions with the best documented cases for strong VTI in D" tend to have higher than average S-wave velocities and strong D" discontinuities (Figure 1c). There are observations favoring slightly tilted (non-vertical) transverse isotropy (Maupin et al., 2005), which results in weak coupling of the SH and SV signals (the fast wave is still close to the SH polarizations), as well as limited regions where SV signals are found to propagate with higher velocities (Vsv) than SH signals (such as in the central Pacific LLSVP, Figure 1c).

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Seismic anisotropy is only viable if heterogeneities (either chemical blobs or pockets of partial melt) are systematically aligned with the flow. Transitions from horizontal to vertical flows may account for SPO transitions from VTI to horizontal transverse isotropy, which can have Vsv higher than Vsh. Efforts continue to improve the characterization of D" anisotropy because it has the potential to reveal ongoing deformation processes occurring in the boundary layer.

Summary

The diverse seismic properties of the D" region appear to demonstrate the presence of heterogeneity at the base of the mantle associated with thermal and chemical boundary layers of a complex dynamical system. There is a predominance of large-scale structures in D", and the strength of heterogeneities at intermediate and large-scales appears to be significantly greater than in the overlying lower mantle. Large low shear velocity provinces (LLSVPs), ultra-low velocity zones (ULVZs), multiple seismic discontinuities, a major phase change, and seismic anisotropy are all fundamental attributes of the D" region. The present day configuration of D" structures represents a "snap-shot" of an evolving system, with some aspects reflecting very long time-scale processes (LLSVPs may have been in place for at least hundreds of millions of years; ULVZs may be the last remnant of an extensive magma ocean that dates back to core formation) and much shorter time scales (post-perovskite lenses may be found in recently downwelled slab materials and seismic anisotropy may be sustained by present day dynamic shear flows). Together with the ongoing role of D" as thermal boundary layer that regulates cooling of the core and as the site of electromagnetic-mechanical coupling of rotation between the core and mantle, the significance of this region for Earth dynamics appears more evident than ever. While debate continues regarding the extent to which mantle material is fluxing between the shallow and deep mantle, evidence has grown to support a significant feedback/control of D" structures on geological processes at Earth's surface.

Bibliography


Cross-references

Core-Mantle Interaction

Mantle Convection

Mantle Plumes

Structure of Earth’s Core

Structure of Earth’s Lower Mantle
Mantle D'' Layer, Figure 1 (a) Schematic cross-section through the Earth indicating large structures in the D'' region (below the red dashed line) above the core-mantle boundary (CMB) (adapted from Trønnes, 2009). The two large low shear velocity provinces (LLSVPs) under Africa and the Pacific are indicated, with thin ultra-low velocity zones (ULVZs) at their base and margins. Areas of upwelling warm mantle surround and overlie the LLSVPs. Areas of relatively cool mantle downwelling are underlain by D'' material with post-perovskite (ppv) occurrence. Detailed seismic S-wave velocity models from both an LLSVP margin and a down-welling region are shown on the right, with the D'' velocity discontinuity seen at depths of 2,600–2,650 km. Both regions have a deeper velocity decrease that may represent conversion from post-perovskite back to perovskite (pv) in the steep thermal gradient above the CMB at 2,891 km depth. (b) S-wave and P-wave velocity models from areas of intense ULVZ under the central Pacific, showing strong velocity reductions below low velocity (LLSVP) regions. (c) Representative anisotropic S-wave velocity models, indicating high Vsh velocities below circum-Pacific regions with strong D'' discontinuities and high Vsv velocities in LLSVP environments.
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