STRUCTURE OF EARTH'S LOWER MANTLE

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Synonyms

Deep mantle; Deep Earth

Definition

Seismic Tomography. An inverse method that utilizes seismic wave travel times and/or waveforms to estimate Earth's seismic velocity and density structure, either regionally or globally.

Forward Modeling. The procedure involving the generation of models that predicts observations, which is frequently used in deep Earth seismology.

Phase Transition. A crystallographic rearrangement of atoms in a mineral that occurs at high pressure.

D″. The depth shell of Earth occupying the lowermost 200–300 km of Earth's lower mantle. (Pronounced "D-double-prime").

Introduction

Earth's interior has three fundamentally distinct divisions: (1) the relatively buoyant and thin outer crust, which averages roughly 6–7 km in thickness beneath oceans and 30–40 km in continents; (2) the mantle, which extends to nearly half way to Earth's center; and (3) the dominantly iron (Fe) core, which has a fluid outer part and a solid inner part. Figure 1 highlights these basic shells, along with a number of additional significant mantle subdivisions. The mantle is divided into an upper and lower part, with the boundary near 660 km depth. The upper mantle has another distinct discontinuity near 410 km depth. As shown in Figure 2, the dominant mineral in the upper mantle is olivine, a magnesium-iron silicate mineral with composition $(Mg,Fe)_2[SiO_4]$, that undergoes phase transitions to higher density mineral forms (or polymorphs) near 410, 520, and 660 km depths. The region between 410 and 660 km is referred to as the mantle transition zone. Below 660 km, mantle silicates undergo another phase transformation, compacting into the perovskite structure, with composition $(Mg,Fe)[SiO_3]$, plus magnesium-iron oxides, (Mg,Fe)O (known as ferropericlase and also referred to as magnesiowüstite in earlier literature). In the lowermost several hundred km of the mantle, a region referred to as D″, perovskite has been shown to undergo an additional phase transition into the "post-perovskite" structure (Murakami et al., 2004 [Science]), and depending on the temperature, post-perovskite might back-transform into perovskite at greater depth, remaining as perovskite down to the CMB (see The D″ Layer Encyclopedia Entry). The lower mantle depth shell accounts for nearly 56% of Earth's volume, and extends from 660 km depth down to the core–mantle boundary (CMB) at 2,891 km depth (and thus includes the D″ layer). The major discontinuities throughout Earth's mantle are thus well-explained by phase transitions in the olivine-perovskite system.

While uncertainties are present in our understanding of the exact compositional make-up of Earth's mantle, it is generally believed that magnesium-iron silicate perovskite is the dominant mineral structure of the lower mantle, possibly accounting for ~80% of the lower mantle, and hence is the most abundant mineral on Earth. This perovskite mineral structure is the same as that occurring in well known electronic and piezoelectric materials, such as barium titanate. A fundamental difference between the silicate minerals of the upper mantle and lower mantle perovskite is that every silicon (Si) atom in perovskite is surrounded by six oxygen (O) atoms (silicon is octahedrally coordinated), whereas for upper mantle silicates

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the silicon is bonded to four O atoms (tetrahedral coordination). Thus, a primary effect of the higher pressure in the lower mantle is that O atoms occupy a smaller volume, thus more can be organized around (coordinated with) Si. This more compact rearrangement of atoms in lower mantle phases means that they have higher density than upper mantle materials, as well as differences in other properties such as the material's stiffness and resistance to shearing. These changes affect the velocities of seismic waves; thus, at depths where phase transitions occur, there are jumps (i.e., discontinuous increases) in seismic compressional and shear wave speeds (referred to as P-wave and S-wave velocities, or V_P and V_S, respectively). Velocity and density depth distributions in Earth's mantle are presented in Figure 2; these values represent an estimation of the globally averaged properties.

The exact depth of a phase transition in any given mineral group depends upon temperature and pressure (and chemical composition). Earlier conceptions of the lower mantle (Birch, 1952) postulated that the lower mantle had a constant composition, and hence the temperature and velocity variations could by described by simple adiabatic compression. However, in light of more recent studies, it is interesting to consider the fact that lateral temperature variations are likely in the lower mantle, because the mantle is convecting, and hence phase boundaries are not expected to be perfectly flat (e.g., Lebedev et al., 2002). Rather, they should have relief that directly relates to the temperature field (or to perturbations in chemical composition, since minerals may transform at different pressures if there are variations or impurities in the mineral composition). The Earth presumably was significantly hotter in the distant geologic past (from heat generated during formation and differentiation of the mantle and core), therefore we expect phase boundaries in the earliest Earth to have been at different depths than today.

Tools for studying the lower mantle

Earth's mass and moment of inertia, determined from orbital and rotational dynamics, provide important information about the planet's internal density distribution. These data, combined with assumptions about starting materials for Earth's formation from analyses of meteorites, have long indicated a predominantly iron core with a silicate rock mantle (Carlson, 2003). Seismic studies early in the twentieth century confirmed the existence of the core (outer and inner), as well as the fact that the outer core is liquid (from the absence of shear waves on the opposite side of the planet following an earthquake, because shear waves cannot propagate in fluids).

A number of Earth science disciplines contribute to our body of knowledge of the lower mantle (and the deep Earth in general). For example, the field of mineral physics includes high pressure laboratory experiments aimed at simulating the pressures and temperatures within the deep Earth. Predictions of the melting temperature of iron at the conditions of the boundary between the inner and outer core (at radius of ~1,220 km), as well as measurements delineating the temperature of the olivine to perovskite plus ferropericlase phase transition at 660 km depth provide two important temperature tie-in points that help to constrain Earth's geotherm; temperature must be extrapolated from these points toward the CMB, where a very large temperature jump occurs. Based on such studies, the top of the lower mantle at 660 km depth is at a pressure of about 23 GPa (1 Pa = 1 N m^{-2} and 10^5 Pa corresponds to approximately 1 atm of pressure) and a temperature of about 1,800 +/− 200 K (e.g., Ito and Katsura, 1989; Frost, 2008). The CMB is at a pressure of about 130 GPa; the temperature, while less constrained, has been recently estimated to be about 4,000 +/− 500 K (Van der Hilst et al., 2007). The temperature jump from the CMB to the outermost core may be as much as 1,000–1,500 K.

A number of notable uncertainties are present that currently preclude precise knowledge of lower mantle temperature, including the amount of heat-producing radiogenic materials, the vigor of mantle convection, the heat flux from the fluid core into the mantle, and important thermal properties of perovskite at lower mantle pressure and temperature conditions (e.g., thermal conductivity, heat capacity, and the coefficient of thermal expansion). However, using a diamond anvil cell high-pressure device to achieve pressures as great as those of the lower mantle and even the core, researchers have recently refined our understanding about two important characteristics of perovskite. As mentioned above, perovskite (*pv)* can transform into a higher pressure (and density) structure termed "post-perovskite" (*ppv*) at D″ pressures (around 120 GPa). Thus, if the systematics of this phase transition can be well defined from laboratory experiments or theory, then seismic mapping of the $pv \rightarrow ppv$ transition depth (as well as that of possible $ppv \rightarrow pv$ back-transformation) adds an additional temperature tie-in point for the geotherm (Hernlund et al., 2005). Another discovery describes a change with increased pressure in the electronic spin state of iron in magnesiowüstite and perovskite (a change from a high-spin configuration with a maximum number of unpaired d-shell electrons to a low-spin configuration in which d-shell electron pairing is maximized). Experiments indicate that this will occur between the depths of 1,000 and 2,200 km (Lin et al., 2007). Current research predicts that this spin transition may result in a softer material, which can thus be more compressed and increase the density of the deeper mantle, possibly affecting convective dynamics.

The vigor of mantle convection plays a central role in the cooling of Earth. The most commonly used parameter to determine if convection is occurring and to describe the strength of convection is the Rayleigh number, *Ra*:

$$Ra = \frac{\alpha g \rho \Delta T D^3}{\eta \kappa},$$

where α is the coefficient of thermal expansion, g is the acceleration due to gravity, ρ is density, ΔT is the non-adiabatic temperature change across the convecting layer (in this case, the whole mantle) of thickness D, η is the viscosity, and κ is the thermal diffusivity. *Ra* in the lower mantle is estimated to be on the order of 10^7; values greater than $\sim 10^3$ indicate that convection is occurring and values as high as 10^7 indicate vigorous convection. Factors such as the temperature dependence of viscosity can strongly affect the style of convection. Thus, numerical convection calculations incorporate our best understanding of Earth's properties and provide important information about the dynamics and evolution of the mantle (and the planet as a whole).

Erupted materials offer an opportunity to study mantle chemistry. Specifically, some hot spot volcanoes are thought to be caused by mantle plumes that originate in the lower mantle. There is current debate regarding whether all hot spots tap the lower mantle, as well as the depth of origin of different plume sources (Courtillot et al., 2003). However, it is widely accepted that magmas from hot spot volcanoes contain isotopes that are either absent or diminished compared to lavas erupted at mid-ocean ridges. This has led to a view that the lower mantle represents a distinct reservoir that has undergone little or no mixing with the upper mantle (Hofmann, 1997). Subsequent and ongoing work continues to challenge that perspective, which we address in the three-dimensional structure and dynamics section below.

Seismic imaging is the primary tool that gives us the ability to map lateral variations of mantle properties from the upper mantle to the CMB. Seismic tomography provides an image of the full three-dimensional heterogeneity field, albeit at relatively long horizontal wavelengths, on the order of 3,000 km or so (e.g., Ishii and Tromp, 1999; Ritsema and van Heijst, 2000; Mégnin and Romanowicz, 2000; Grand, 2002). Variations in seismic velocity as well as density (Trampert et al., 2004; Ishii and Tromp, 2004) have been mapped, and when compared to surface tectonics, help to depict convective flow in the interior.

Information about the small-scale heterogeneity field is provided by a number of forward-modeling seismic studies. For example, some studies have suggested that small-scale scatterers exist throughout the lower mantle (Hedlin and Shearer, 2000). Other studies find evidence for discrete reflectors in some locations, particularly beneath subduction zones (Rost et al., 2008; Kito et al., 2008). The exact nature of such small-scale heterogeneity is unknown, but may indeed relate to an incompletely mixed mantle, or heterogeneities entrained from the top (dense things falling) or the bottom (buoyant things rising).

Three-dimensional structure and dynamics

For decades, it has been known that Earth's mantle contains significant lateral variations in seismic properties, which are due to variations in temperature and or chemical composition compared to the local average properties. Results from seismic tomography depict V_P, V_S, and ρ changes throughout the mantle. Variations are neither expected nor detected in the fluid outer core; the extremely low viscosity and relatively fast convection promote homogenization (Stevenson, 1987). Seismically detected mantle heterogeneity is the strongest in the outermost few hundred kilometers of the mantle (i.e., near the planet's surface), due to the strong variations in temperature and composition associated with plate tectonic and mantle convection processes (Masters et al., 2000). The next most seismically heterogeneous depth shell is the D″ region at the base of the mantle (see Encyclopedia entry on The D″ layer). Figure 3 shows seismic velocity variations in the lower mantle. D″ silicate rock is juxtaposed against the fluid iron outer core, which represents roughly a 75% increase in density. Thus, the mantle side of the CMB can accommodate long-lived stable structures over a wide range of densities (between the mantle and core density); it is possible that cumulates denser than average lowest mantle silicates can survive entrainment by the convective currents in the overlying mantle (e.g., McNamara and Zhong, 2005). However, other possibilities are viable (Deschamps et al., 2007).

The lower mantle above D″ displays variability in seismic properties, but at a much weaker level than that imaged at the top and bottom of the mantle. In some regions it is plausible that low amplitudes of mid-mantle heterogeneity may reflect our limited ability to confidently image the mantle there (due to a lack of seismic information because earthquakes and seismic recorders are not uniformly distributed on Earth). Nonetheless, all seismic tomography studies to date agree that heterogeneity is greater at the top and bottom of the mantle relative to the middle of the mantle.

Plate tectonics involves the creation of plates at mid-ocean ridges, and destruction or consumption of plates at subduction zones, where the cold and dense oceanic crust and lithosphere (compared to the surrounding mantle) descend into the interior. Tomographic analyses have shown that lineations in high-velocity wave speeds beneath subduction zones (e.g., Grand et al., 1997) are consistent with cold material subducting deep into the lower mantle. While the penetration depth of subducting slabs is not adequately constrained beneath all subduction zones, it is widely accepted that most slabs descend through the 660 km discontinuity, in some cases reaching to the CMB (such as beneath the Caribbean). It is important to understand the large-scale long-term flux of material from Earth's surface to great depths in the interior because of the importance for long-term (geological time) effects on surface volatiles, the atmosphere, and global climate.

The amount of mass flux between the upper mantle down into the lower mantle depends on several poorly known quantities such as the viscosity of the descending slab and mantle, the viscosity increase at the 660 km discontinuity, as well as the degree of viscous coupling

between the oceanic lithosphere and underlying asthenosphere (before and after subduction). Time-integrated mass transfer into (and out of) the lower mantle plays a role in long-term mixing and lower mantle residence time of deep mantle minerals. For example, weak viscous coupling between slabs and the surrounding mantle predicts lower flux rates into (and out of) the lower mantle, and hence less mixing between the upper and lower mantle. A strong coupling between the slab and mantle predicts the opposite. Current data and predictions do not yet distinguish between these possibilities.

An analogous dependency between mixing and convective parameters exists for the bottom of the mantle, where recent work argues for a chemically distinct origin of tomographically identified large, low shear wave velocity regions (Garnero and McNamara, 2008). Convective currents associated with subduction sweep basal dense material to regions away from downwellings, forming thermochemical "piles" (Figure 4) (McNamara and Zhong, 2005). The contrast in properties (e.g., density, viscosity, temperature) between piles and surrounding mantle will determine the morphology and vertical extent of the pile material, as well as the degree of entrainment (and hence its evolutionary behavior). The two, nearly antipodal low shear velocity regions, one beneath the central Pacific and the other beneath the southern Atlantic and Africa (Figure 3), are accompanied (in certain areas) by low-velocity conduits that are associated with mantle plumes (Montelli et al., 2004). Thus, the present-day large-scale structure and circulation pattern of the lower mantle represent a time-integrated effect of anomalous temperature and/or chemistry in Earth's lowermost and uppermost mantle boundary layers (D″ and the lithosphere, respectively).

At smaller scale lengths, seismic studies have found evidence for seismic wave scattering. The imaged size of heterogeneities in the lower mantle ranges from a kilometer to tens of kilometers in scale (e.g., Vidale and Hedlin, 1998; Wen and Helmberger, 1998). This observation indicates chemical anomalies at a spectrum of physical scales and a mantle that is not fully mixed. Indeed, analyses of magmas from hot spot volcanoes have yielded characteristic isotopic signatures distinct from those of mid-ocean ridge basalts, arguing for unique, possibly isolated deep mantle reservoirs that feed mantle plumes. Irregular convective patterns (e.g., see Figure 4) are consistent with such heterogeneities spreading through the lower mantle as well as being entrained into mantle plumes, but not necessarily in a systematic fashion (since convection patterns appear multi-scaled and may be complex). Alternatively, scattering of seismic energy can occur from small pockets of partially molten mantle material. This scenario has been motivated by the detection of thin (a few km) laterally discontinuous layers right at the CMB, called ultra-low-velocity zones (ULVZs). ULVZs have been argued to contain some degree of partial melt, and hence offer a plausible source of scatters composed of melt pockets (whether or not they are of a distinct chemical composition).

Future progress

As seismic sensors are deployed in new regions across Earth's surface, new geographical regions will be sampled with greater certainty, and thus our understanding of global processes will greatly improve. As sensor deployments become denser (with smaller distances between sensors), Earth's deep structure can be imaged with a much greater resolution. Thus small-scale structures and processes can be inferred with greater certainty and tied to estimations of global processes. The seismic work only maps present-day structure, which must be put in a dynamical and evolutionary framework with the predictions from geodynamical convection calculations, which in turn must first be informed by an understanding of the material properties. The latter comes from the field of mineral physics, both in laboratory experiments at high temperature and pressure, as well as with computer simulations of material behavior at the atomic scale. The time evolution of Earth is also informed by geochemical analyses of erupted materials and meteorites. Thus, future work that advances our understanding of the structure, dynamics, and evolution of Earth's interior will be multidisciplinary in nature.

Summary

Earth's lower mantle represents the largest volume of any depth shell on Earth. It is unique in that its chemistry, structure, dynamics, and evolution represent a time-integrated effect of the chemistry and dynamics of the surface (lithosphere, asthenosphere) and lowermost mantle (D″, ULVZ, CMB) boundary layers. The degree to which the lower mantle is recycled into the upper mantle depends upon many poorly known convective parameters, such as the viscosity and viscous coupling of descending slabs, as well as material properties, such as the nature and origin of dense deep mantle chemically distinct piles. Future work of improved seismic imaging coupled with continued advancements in other deep Earth disciplines, such as geodynamics, mineral physics, and geochemistry, will greatly help to reduce uncertainties in our understanding of Earth's evolutionary pathway, and present-day structure and dynamical state.

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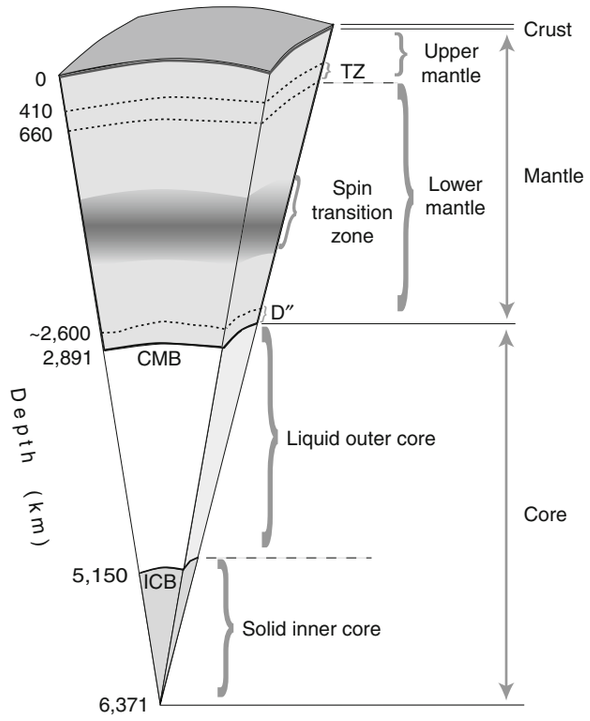
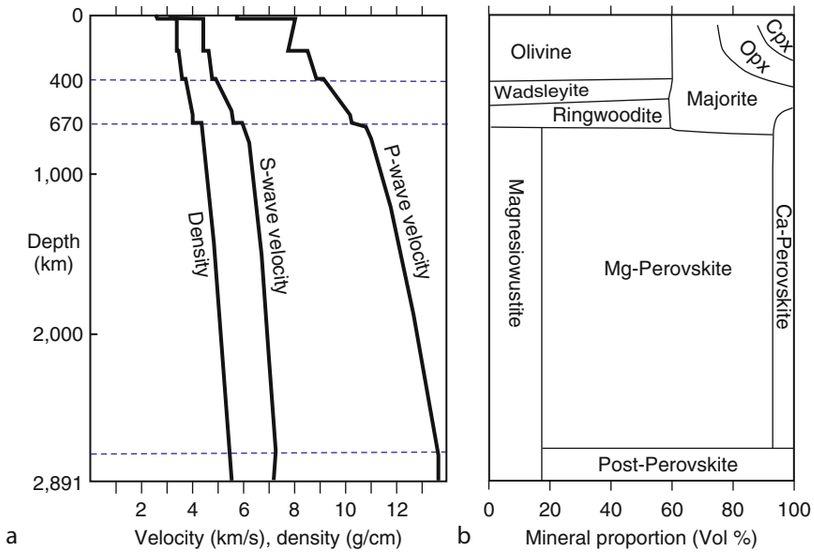
Cross-references

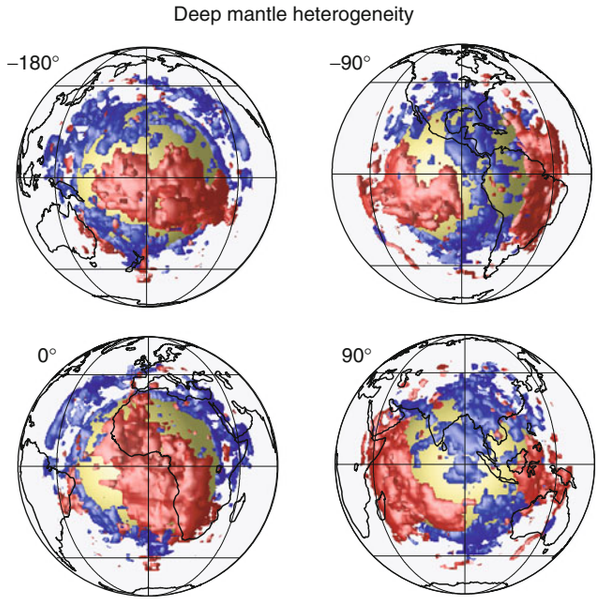
Core–Mantle Interaction
Mantle Convection
Mantle D″ Layer
Mantle Reology
Structure of Earth's Core
Upper Mantle Structure



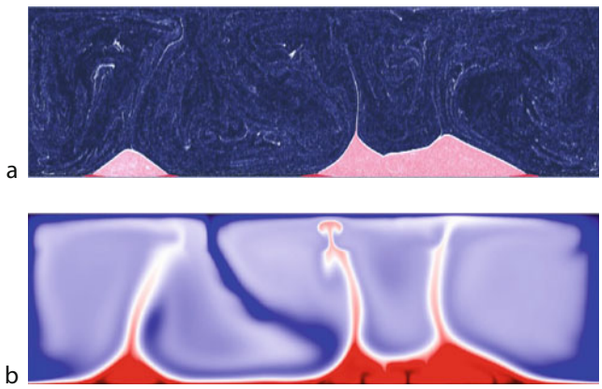
Structure of Earth's Lower Mantle, Figure 1 Major depth shells of Earth, along with a number of subdivisions. TZ = transition zone (the upper mantle between 410 and 660 km depth); CMB = core–mantle boundary; ICB = Inner core boundary.



Structure of Earth's Lower Mantle, Figure 2 (**a**) Variations in seismic properties of the Earth's mantle with depth, from the surface to the core–mantle boundary, showing the major discontinuities in P-wave velocity, S-wave velocity, and density. (**b**) Mineralogical makeup of the mantle. Cpx = clinopyroxene; Opx = orthopyroxene.



Structure of Earth's Lower Mantle, Figure 3 Heterogeneity in the deep mantle at a depth of 2,800 km is seen in the tomographically derived shear velocity wave speed variations (Ritsema and van Heijst, 2000). Iso-surfacing at the + 0.7% (*blue*) and −0.7% (*red*) levels show the higher and lower velocity regions, respectively. Two large low shear velocity provinces are present, and high velocities tend to be located below present-day (or recent past) subduction.



Structure of Earth's Lower Mantle, Figure 4 Numerical geodynamics calculations for a model mantle consisting of three distinct chemistries are shown for the whole mantle, from Earth's surface to the core–mantle boundary. Panel (**a**) displays the chemical field, showing the bulk of the upper and lower mantle in blue, as one chemistry type, dense lower mantle piles (*pink*) as a second distinct chemistry, and thin ultra-low-velocity zones at the core mantle boundary (*red*) that accrue near the pile margins. (**b**) The temperature field associated with (**a**) is shown. Red and blue are hotter and colder regions, respectively. The dense piles can be stable for billions of years, though a low level of entrainment is constant, as evidenced by the white streaks throughout the mantle in panel (McNamara et al., 2010).