McGRAW-HILL YEARBOOK OF Science & Technology

2002

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Ultralow-velocity zones (seismology)

Scientists who analyze waves that emanate from earthquakes (seismologists) have recently discovered new methods to study the boundary between the Earth's mantle and core in unsurpassed detail. Some 2900 km (1800 mi) below the Earth's surface, the core-mantle boundary contains important clues to many unanswered questions about the Earth's formation, evolution, and present internal processes. Analysis of seismic waves has revealed that, in some places, there is a thin mushy layer right at the core-mantle boundary. Seismic waves that travel in this layer are slowed down, giving rise to the name ultralow-velocity zone (ULVZ). The correlation between the geographic locations of the core-mantle boundary mush zones and some types of volcanoes suggest that ULVZs may be the source of volcanoes in regions such as Hawaii and Iceland. The importance of ULVZs in both mantle and core processes is apparent; possible physical scenarios include melting of the very base of the Earth's mantle, a blurring of the core-mantle boundary itself, and even sedimentation processes in the outermost core on the underside of the core-mantle boundary.

Seismology as an imaging tool. The most direct approach for studying the intricacies of the Earth's interior is through seismic wave analysis. Such waves propagate through the entire interior of the Earth. Just as the path of light bends as it passes from air into water, seismic energy passing from the Earth's mantle into the core experiences slight changes in direction. Some of this energy bounces off interfaces with different bulk Earth properties (reflection), some of it travels straight through material and can bend (refraction), and some of it travels along boundaries between distinctly different materials (diffraction).

SPdKS waves. A demonstration of these properties of seismic waves comes from a particularly useful seismic wave for deep Earth study called SKS. It traverses the Earth's mantle as an S-wave (secondary or shear wave), converts to a P-wave (primary or compressional wave) at the core-mantle boundary, and travels through the core as a P-wave (represented by the symbol K in SKS), returning to the mantle for the final leg of its journey as an S-wave (**Fig. 1*a***). When SKS encounters the core-mantle boundary at a critical propagation angle, its energy completely converts to a P-wave that diffracts (d) horizontally along the core-mantle boundary, then dives into the core and follows a path similar to SKS. This wave is called SPdKS, and permits the investigation of the details of the core-mantle boundary at localized spots where SPdKS enters and exits the core. SPdKS is directly affected by any changes in seismic velocity at the core-mantle boundary, which alters the short segment of diffracting P-wave energy (Pd in Fig. 1*a*). To document peculiarities in SPdKS behavior, it is compared to SKS, which travels a very similar path through the Earth. In fact, it was through study of SKS waves that SPdKS behavior was first noted.

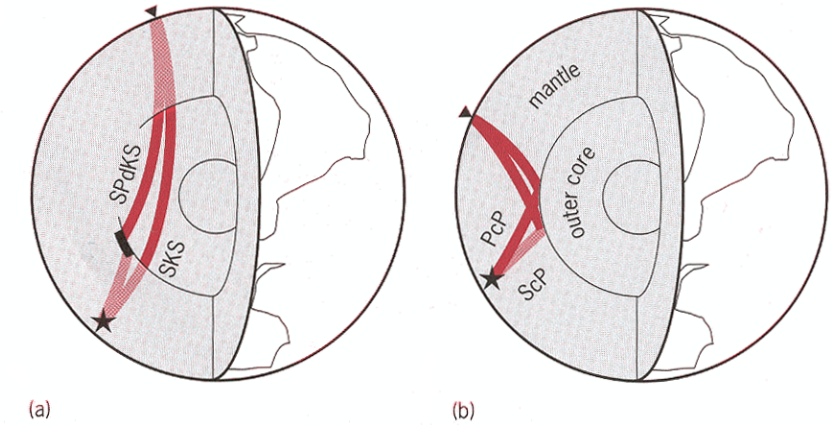

Fig. 1. Cross section of the Earth showing the mantle and core. (*a*) Seismic waves SKS and SPdKS. The hypothetical earthquake (star) generates the energy that travels through the Earth to the seismographic recorder (triangle). The short black segment of the SPdKS ray path enables study of any possible layer between the mantle and core. (*b*) Seismic waves ScP and PcP. The energy from these waves reflects off the core-mantle boundary. If any additional layering is present, seismic energy will reflect off that as well, resulting in precursory energy arriving at the seismic recorder before ScP or PcP.

ScS, ScP, and PcP waves. Seismic waves reflected off the core-mantle boundary (identified by the symbol c) are also useful for detecting thin layering at the bottom of the mantle. S- and P-waves that reflect off the core-mantle boundary, as well as S-waves that convert to P-waves upon reflection, show precursory energy if any low-velocity material exists at the core-mantle boundary. Seismic energy bounces off the top of the ULVZ layer and arrives at the surface before the energy that reflects off the core-mantle boundary. Recent research has used these reflected waves, along with SPdKS, to study ULVZ structure.

Synthetic seismograms. The approach most commonly used in characterizing ULVZ structure is to compare seismic observations with predictions. Observations are the seismic waves emitted from earthquakes and recorded by seismometers around the world. Predictions are computations of what a seismogram would look like for a given model of the Earth, using principles of math and physics that describe how energy propagates through an elastic medium (the Earth). These predictions are synthesized on powerful computers, and are called synthetic seismograms. This process of comparing synthetic to observed seismograms is called synthetic modeling; if the data and predictions are similar, then the model of the Earth used in the calculations is a possibility.

Geographic distribution of ULVZ. Earthquakes predominantly occur in thin belts at the Earth's surface, which define the boundaries between 15 or so plates of the outermost shell of the Earth (the lithosphere). These earthquakes are recorded by seismometers—sensitive devices that detect ground motion—and are predominantly restricted to continents which cover about one-third of Earth's surface area. The geographical limitations of uneven earthquake and

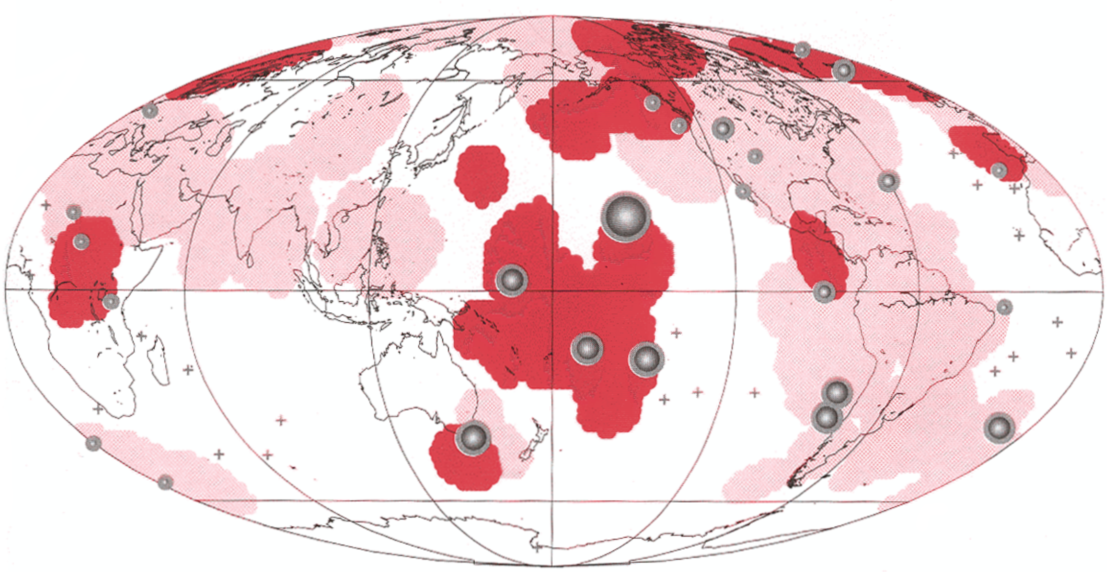

Fig. 2. Geographic distribution of ULVZ (dark color) and regions where ULVZ have not been detected (light color). These are compared to surface locations of hot-spot volcanoes (circles), which correlate well with locations of ULVZ.

seismometer distribution limit the regions of the deep interior that can be probed. Nonetheless, just under one-half of the surface of the Earth's core-mantle boundary has been probed for ULVZ structure. Roughly 25% of the sampled core-mantle boundary shows evidence for the presence of ULVZ. These areas (**Fig. 2**) are strongly correlated with regions at the surface that possess "hot-spot" volcanism—volcanoes containing magma thought to originate in the deep mantle. Regions lacking ULVZ evidence are strongly correlated with past or present subduction zones—regions where cool oceanic lithosphere plunges into the Earth's mantle.

This first-order correlation suggests a link between ULVZ occurrence and large-scale mantle convection. Relatively cold downwelling motions in the deep mantle suppress ULVZ creation, while hot material rising from the core-mantle boundary creates hot-spot volcanism and supports creation of the thin anomalous zones.

Origin of the ULVZ. The earliest ULVZ studies in the mid-1990s documented anomalous seismic data, and modeled it with low-velocity layering at the very base of the mantle. These first attempts to explain the data invoked ULVZ layers of 10–40 km (6–25 mi), showing seismic velocity reductions of 10% below "normal" mantle velocity values at those depths. Strong variations in ULVZ properties were also noted at that time. Subsequent studies have shown that much thinner layers (as thin as 1–3 km or 0.6–2 mi) can also explain some of the data, if the properties of the layer are much more extreme in comparison to the mantle. Several scenarios for the physical nature of the ULVZ have been proposed.

Partial melt of the base of the mantle. The apparent geographic correlation of ULVZ distribution with surface phenomena linked to large-scale mantle motions implies a thermal origin of the ULVZ. If the ULVZ represents a partial melt of some deep mantle constituent, then small-scale instabilities in this layer can combine to give rise to mantle plumes which feed hot-spot volcanoes. Cold downward currents in the mantle, such as those beneath subduction zones, would cool the deep mantle, preventing melting of mantle material.

Thin transition zone from mantle to core. Recently, models containing a mushy zone between the mantle and core have produced synthetic seismograms that correlate particularly well with some observations. This type of model differs from a "pure" ULVZ, in that it involves a smoother transition from the mantle to the core. In this scenario, chemical reactions between the silicate mantle and liquid iron alloy in the outer core result in a thin mixing zone (1–3 km or 0.6–2 mi thick) that "blurs" the core-mantle boundary. Thus this model is referred to as a "fuzzy" core-mantle boundary.

Thin outermost core layering. The liquid outer core of the Earth is predominantly iron, along with a minor portion of some less dense elements (a lighter component is required to satisfy the observation that the core is slightly less dense than pure iron). As the Earth cools, the solid inner core of the Earth grows; this process releases the lighter elements into the overlying liquid outer core. This process could result in the "underplating" of the lighter elements at the core-mantle boundary (a sedimentation process) since they should be significantly more buoyant than iron. It is expected that this layering would be nonuniform, since the core-mantle boundary is expected to have topography induced from convection currents in the overlying mantle, which would concentrate more sediment in "hills" on the core-mantle boundary. Seismic modeling has shown that sediment thicknesses of 1–2 km (0.6–1.2 mi) can explain the observed seismic anomalies.

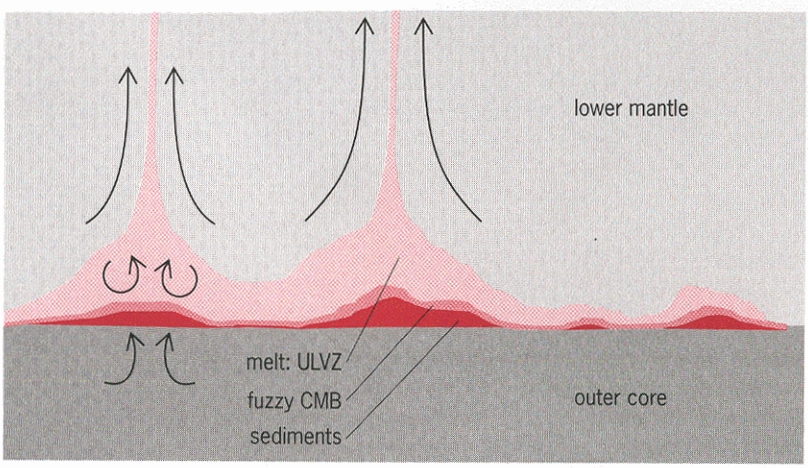

Fig. 3. A hypothetical scenario involving all three types of low-velocity layering: melt on the mantle side of the core-mantle boundary provides the genesis of mantle plumes that feed surface volcanism; sediments accrue underneath the core-mantle boundary beneath hills in the boundary; and the actual boundary itself is blurred due to chemical interaction between core and mantle material.

The real Earth. Seismic imaging methods are always improving, and combining different methods greatly reduces uncertainties for any given model. Presently, each of the above scenarios is a viable explanation for the anomalous seismic signals. It is possible that the Earth may be a combination of all three structures (**Fig. 3**). The geographic correlation of ULVZs and surface hot spots strongly points to partial melt of the base of the mantle as an explanation. Laboratory evidence for chemical reactions between mantle and core material points to a core-mantle transition zone as a likely candidate (a fuzzy core-mantle boundary). The growth of the inner core as the Earth cools is known to release lighter elements into the outer core, opening up the possibility of sedimentation on the underside of the core-mantle boundary. The responsibility for deep-Earth scientists is to better constrain what degree each of these phenomena contributes to the anomalous waves that seismologists record at the Earth's surface. *See also* AFRICAN SUPERPLUME.

For background information *see* EARTH INTERIOR; EARTHQUAKE; LITHOSPHERE; PLATE TECTONICS; SEISMOLOGY in the McGraw-Hill Encyclopedia of Science & Technology.

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