PERSPECTIVES: GEOPHYSICS

Earth's Enigmatic Interface

Edward J. Garnero and Raymond Jeanloz

At the boundary between Earth's rocky mantle and its metallic core, a dramatic change in physical properties occurs. Density and seismic wave velocities change more substantially at this boundary than between the air and rock at Earth's surface. Moreover, the bottom of the mantle, like its top, exhibits strong lateral heterogeneity in properties such as seismic wave speeds. This horizontal variability can both cause and result from the processes controlling Earth's internal evolution, such as mantle convection and melting.

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High-resolution seismological studies, in which the seismic rays that have traversed the lowest regions of the mantle are analyzed, demonstrate the complexity of the core-mantle boundary (*1*). Of the around 45% of the core-mantle boundary that has been recently probed for layering complexities, nearly 12% indicate an anomalous boundary layer structure (*2*). But distinguishing between different models of the boundary from seismic data turns out to be difficult, and there are several competing models for the boundary layer structure.

Thin patches with ultralow seismic wave speeds are observed in some regions of the boundary, and these have been interpreted as signs of partial melting at the base of the mantle (*3*). High-pressure laboratory experiments have offered some support for this interpretation (*4*, *5*). A correlation between these ultralow-velocity zones (ULVZ) and volcanic hot spots at the surface has also been proposed (*2*). The ULVZ layer is believed to be about 5 to 50 km thick on the mantle side of the core-mantle boundary. Compressional and shear wave seismic velocity are substantially reduced in this layer, possibly by as much as 10 to 20% and 10 to 50%, respectively, relative to the overlying mantle (*6*). The ranges in ULVZ velocities and thickness are large because the velocities, thickness, and density are not well constrained. This problem is further enhanced with the addition of boundary layer topography (*7*).

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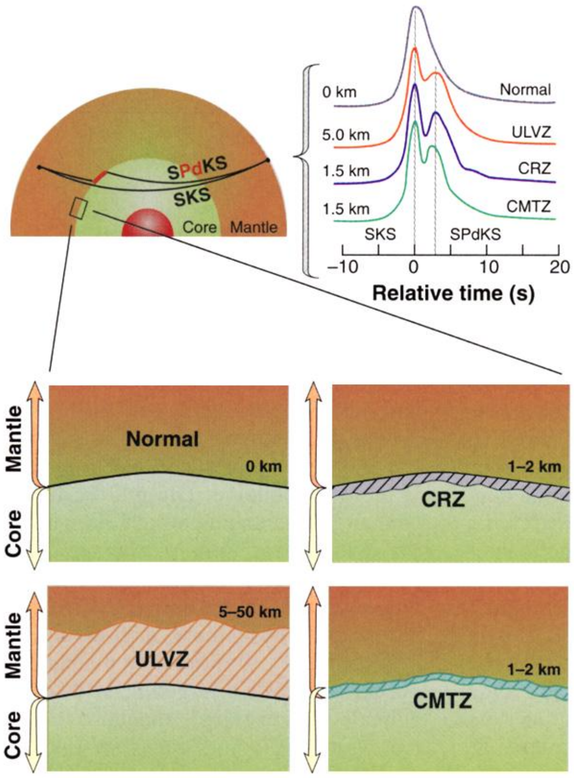
The interpretation of seismic waveforms is often ambiguous. Seismic wave speeds of the outermost core are much slower than those of the lower mantle, largely because the former is liquid whereas the latter is crystalline. Therefore, instead of invoking a large reduction in wave velocities (associated, for example, with partial melting) at the base of the mantle, one can alternatively interpret the seismic data in terms of a boundary layer containing both mantle and core material—essentially a blurring of the core-mantle boundary. Synthetic seismograms for such a core-mantle transition zone (CMTZ) match the waveform predictions of a ULVZ structure quite well (see upper right panel in the figure) and are easily distinguishable from "normal" Earth models without boundary layer structure. Therefore, features interpreted as ULVZs may instead be caused by infiltration between the crystalline mantle and liquid outer core in regions.



Possible mantle-to-core transitions. Seismic waves sensitive to boundary layer structure at Earth's core-mantle boundary (CMB), such as SKS and SPdKS waves (**upper left**), produce diagnostic waveform behavior, such as large delays in SPdKS relative to SKS (**upper right**). First-order differences are apparent between models lacking strongly reduced seismic velocities ("normal") and models with distinct boundary layer structure (ULVZ, CRZ, and CMTZ), but distinguishing between different types of ultralow-velocity layers is difficult. The boundary layer thickness for the different models must be adjusted to fit the data; relatively thicker layers are needed for the ULVZ layers, compared with the thin structures of the CRZ or CMTZ layers.

Yet another model does not invoke any change in mantle properties but rather proposes a thin zone of finite rigidity at the top of the outer core (see the figure). Such a core-rigidity zone (CRZ) could result from crystallization at the top of the core. Isolated patches of core-side rigidity may be protected from the relatively rapid core currents, if they are located beneath positive core-mantle boundary bumps that are at least 1 to 2 km deep. It is important to note that all of these structures (ULVZs, CMTZs, and CRZs) are modeled as being small in thickness (around 0.5 to 20 km) and large in width (greater than 100 to 200 km) relative to the about 20- to 80-km wavelengths of the seismic rays being used to image the core-mantle boundary.

There is no reason to insist that there can be only one valid interpretation for the "ULVZ signature" in the seismic data. Different interpretations may apply to different regions of the core-mantle boundary, or a combination of interpretations could apply to all. For example, infiltration of the mantle by outer-core liquid (presumably in regions where the core-mantle boundary is slightly depressed) could readily induce partial melting of the lowermost mantle.

The alternative interpretations of the seismological data do, however, have different consequences. Ultralow velocities at the base of the mantle suggest higher than average temperatures (or the presence of fluxing components), whereas crystallization of the outermost core suggests lower than average temperatures at the mantle-core interface. This difference has implications for mantle dynamics (*2*) and for the core dynamo that produces the geomagnetic field (*8*). Topography and infiltration have geodynamic and geochemical implications, respectively, for the evolution of Earth's interior and may be related to geodetic observations (*9*, *10*).

Different seismic probes of the core-mantle boundary have different abilities and limitations in resolving thin boundary layers containing super low seismic velocities. For example, seismic waves that travel down into the mantle and bounce off the boundary back toward the surface inherit additional small seismic arrivals due to energy that reflects off the top surface of the ULVZ. If the transition from the ULVZ to the overlying mantle is not sharp, these reflections are significantly subdued. On the other hand, the SPdKS seismic wave has small segments of energy that diffract along the core-mantle interface (see upper left panel in the figure). SPdKS is more sensitive to lowered wave speeds in the boundary layer than to the sharpness of the top of the ULVZ. Recent efforts (*11*) point to regions lacking highly anomalous ULVZ structure, suggesting instead that complex CMB boundary layer structure is intermittent in the lateral direction.

One conclusion is constant among all models. However the ULVZ signature observed in the seismological waveforms is interpreted, it appears to require strong physical and chemical interactions between Earth's mantle and its core. As more high-quality seismic data are collected and analyzed, with multiple types of seismic waves sampling specific spots of the core-mantle boundary, we will be in a better position to resolve this apparently exotic boundary deep within our planet.

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PERSPECTIVES: PLANT GENETICS

A Tomato Gene Weighs In

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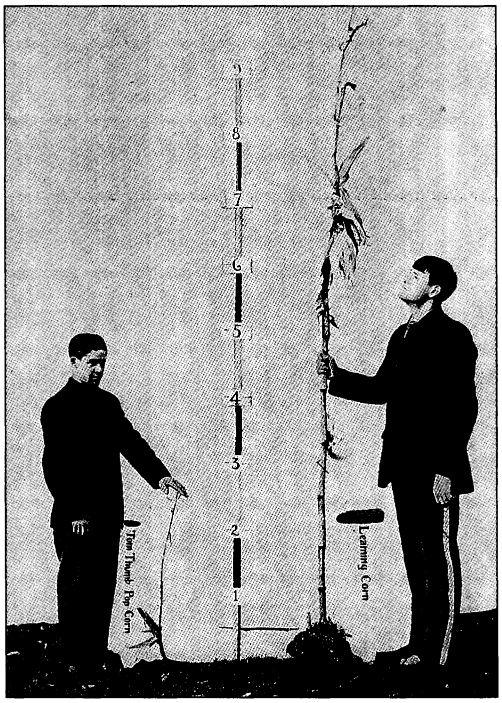
Look at any group of people and you will see that they differ from one another in a continuous or quantitative fashion. Short to tall or slender to stout, the variations are continuous. Such quantitative variation has been the raw material for both Darwinian evolution under natural selection and crop improvement under human selection (see the figure, this page). As such, quantitative variation has occupied the interest of geneticists for nearly a century (*1*). Yet, progress in understanding how genes control quantitative traits has been slow, and the field of quantitative genetics has been largely occupied with making statistical descriptions of the underlying genes, never really knowing what genes are involved. On page 85 of this issue, Frary, Tanksley, and their colleagues (*2*) break through this impasse with their report of the molecular cloning of one of the genes (*fw2.2*) responsible for the quantitative difference between the small-fruited wild tomatoes of Mexico and their monstrous cultivated counterparts arrayed on the grocer's shelf (see the figure, next page).

The journey to clone *fw2.2* began in the late 1980s when Tanksley's laboratory at Cornell University reported the first genome-wide scan for quantitative trait loci (QTLs), the genes that control quantitative traits (*3*). Conceptually, QTL scans or mapping experiments are straightforward. For tomato, simply cross the wild (*w*) and cultivated (*c*) types and then self-pollinate their hybrid to make an F_2 generation that will have a continuous range from small- to large-fruited plants. By having "markers" throughout the genome, one can observe whether a particular F_2 plant has two cultivated variants or alleles (*cc*), two wild alleles (*ww*), or one of each (*cw*) at various points (markers) along the chromosomes. If a QTL for fruit weight lies near a particular marker, then F_2 plants with two *w* alleles at that marker will have, on average, smaller fruits than plants with two *c* alleles. By this method, the Cornell team identified at least 28 QTLs controlling the difference in fruit weight between wild and cultivated tomato, one of which is *fw2.2* (*4*). By refined mapping studies over the past decade, they localized *fw2.2* to a narrow chromosomal region (1/10,000th of the genome) (*5*), setting the stage for cloning of this gene.



The long and short of it. Photograph from a 1914 article by geneticist Albert Blakeslee showing extremes in quantitative variation for height in corn and students at Connecticut Agricultural College. [Source: (*9*)]

To fully appreciate this feat, one needs to understand the complexities of quantitative inheritance. If fruit size were controlled by a single gene with alleles *S* for small and *s* for large, then the progeny of crosses between wild and domesticated tomato would segregate in nice 3:1 ratios of small- to large-fruited plants. For such discrete traits, one can infer the "genotype" (*SS* or *Ss* versus *ss*) by observing the "phenotype" (large or small). Under these circumstances, geneticists have an impressive arsenal of tools that can make gene cloning a summer project for an undergraduate student. For quantitative traits, the situation is more complex. First, quantitative traits are controlled by multiple QTLs, and plants with the same phenotype can carry different alleles at each of many QTLs. Second, plants with identical QTL genotypes can show different phenotypes when raised under different environments. Finally, the effect of one QTL can depend on the allelic constitution of the plant at other QTLs. For these reasons, one cannot infer the genotype from the phenotype, and one must construct specialized genetic stocks and grow them in precisely controlled environments as a prelude to cloning.

Many previous reports have implicated specific genes in the control of quantitative traits. For example, several studies point to an association between *ApoE* in humans and coronary heart disease (*6*); another report links *scabrous* to the number of cuticular bristles in fruit flies (*7*). These studies used a statistical ap-

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