

GEOPHYSICAL DYNAMICS AT THE CENTER OF THE EARTH

New studies are revealing the dynamics of the Earth's deep interior to a degree that could hardly be imagined even a few years ago. A combination of geophysical observations (mostly seismological, geomagnetic and geodetic) and new laboratory and computational results has revolutionized our ability to understand what happens at the core of our planet.

The basic structure of the

Earth—a metallic core surrounded by an oxide shell (the rocky mantle and the crust) 2890 km thick—forms the backdrop for this work. (See the box beginning on page 23.) The metallic core is partly molten and partly crystalline. The 2260-km-thick molten outer core, which produces the Earth's magnetic field, surrounds the crystalline inner core, whose radius is 1215 km.

Rotation at the center

One of the most stunning discoveries is that the inner core may well be rotating faster than the Earth's surface by about 1–3 degrees per year. (See figure 1.) The significance of this observation is that it offers us the first means of determining the motions throughout the fluid region in which the geomagnetic field is created. Indeed, it is the only known example of a time-dependent seismological structure deep inside the Earth, and the observational result turns out to be in excellent agreement with recent theoretical predictions by Gary Glatzmaier (Los Alamos National Laboratory) and Paul Roberts (University of California, Los Angeles).^{1,2}

These observations are made possible by the remarkable fact, discovered a dozen years ago, that the inner core is acoustically anisotropic; that is, seismic waves travel a few percent faster along the polar axis than they do in the equatorial plane. The source of this anisotropy is not entirely understood, but it seems to be related to the hexagonal close-packed (hcp) crystalline structure of the inner core. The available high-pressure laboratory data and state-of-the-art quantum calculations³ suggest that hcp is indeed the stable form of iron under the conditions prevailing in the Earth's inner core.

We (the authors) believe that the most plausible

The Earth's iron core and its boundary with the rocky mantle are very active regions. Now we can see what's going on down there with unprecedented clarity.

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explanation for the observed anisotropy is that solid-state convection of the inner core leads to texturing. That is to say, a preferred orientation of the hcp iron crystals causes the directional dependence of the seismic-wave velocities.⁴ (See figure 2.) Texturing is common in polycrystalline media that have been deformed—for example, ice in a glacier. The nonrandom orientation of the crystals can

lead to strong directional dependences of the elastic properties. Indeed, recent experiments on the effects of shear stresses at ultrahigh pressures demonstrate that hcp iron can develop an exceptionally strong texture at the megatop pressures of the Earth's core.⁵

Why the anisotropy pattern of the inner core should be oriented roughly along the Earth's rotation axis is not entirely clear. It might be due to the pattern of heat loss within the outer core (discussed below). Or it might result from a slight asphericity of the inner core due to the stresses associated with the core's internal convection.

Actually, the direction of fastest seismic-wave velocity through the inner core is tilted by nearly 10° from the Earth's rotation axis.⁶ That finding comes from the analysis of thousands of travel times for seismic waves penetrating the inner core. The anisotropy-axis tilt thus discovered provided the first opportunity to examine the longitudinal orientation of the inner core as a function of time.

This opportunity was seized last year by Xiaodong Song and Paul Richards at Columbia University, who analyzed a smaller set of high-quality seismic records spanning a time period of 30 years.⁷ They clearly observed a time dependence in the travel times for seismic waves passing through the inner core. At the same time Harvard geophysicists Weijai Su and Adam Dziewonski were reexamining the tomographic images produced by inversion of this large data set. These were the images that had revealed a tilt of the inner-core anisotropy axis, and now the Harvard-Berkeley group was searching for any evidence of time variation of that tilt.⁸

Both studies led to the conclusion that the inner core appears to rotate 2 ± 1 degrees per year faster than the Earth's surface. But because the data span only a fraction of a full rotation, inferences about long-term differential rotation are still necessarily tentative. Furthermore, many aspects of these observations require further verification, and it is perhaps fair to say that either study, on its own, might be viewed with skepticism. Nevertheless, it is significant that two completely independent data sets,

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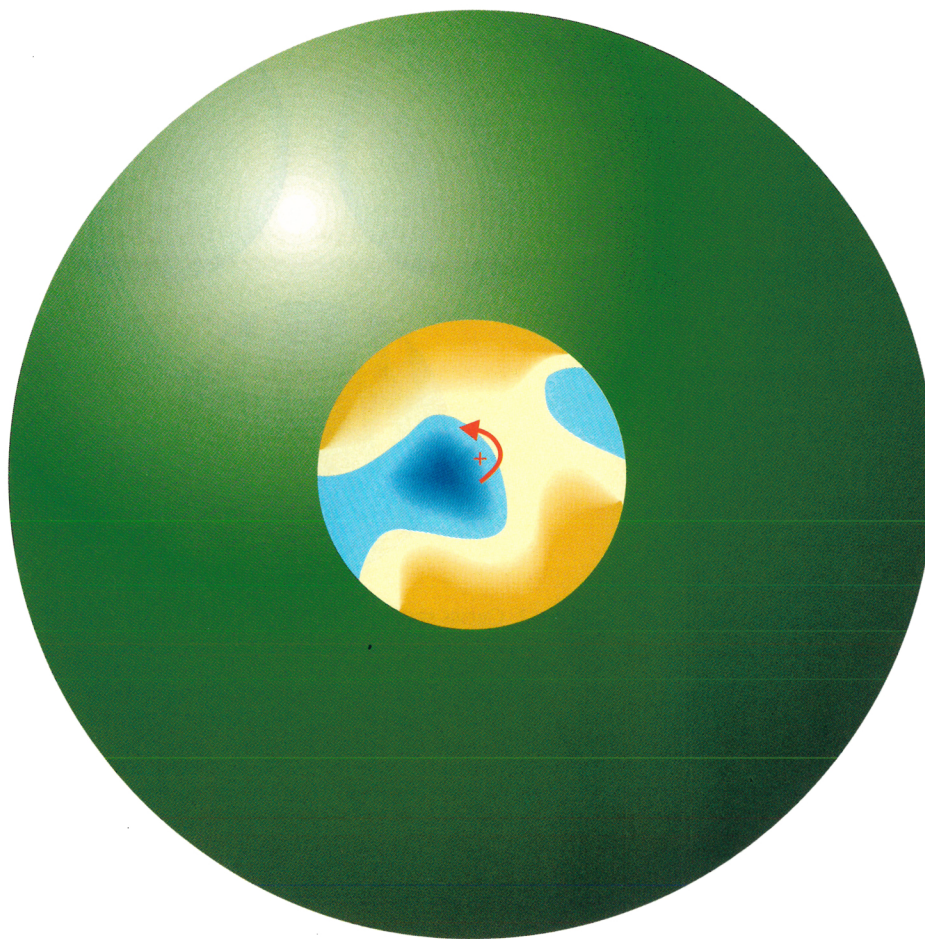


FIGURE 1. EARTH'S SOLID INNER CORE, seen from the north through the liquid outer core (shown green). The color code indicates the variation of seismic-wave velocity with direction through the inner core, from fastest (dark blue) to slowest (dark tan). The axis of fastest seismic velocity, which is tilted by about 10° from the Earth's rotation axis, seems to precess eastward, relative to the Earth's surface, by about two degrees per year, as indicated by the red arrow. (Adapted from ref. 8.)

How Do We Know What's Inside?

The nature of the Earth's deep interior is primarily deduced from seismological, geomagnetic and other geophysical observations. Here we summarize the sometimes indirect arguments used to characterize the main features of the core:

- **The outer core is molten.** Three lines of evidence, the first two from seismology, document this fact. First, horizontally polarized shear waves (transverse elastic waves with horizontal particle motion) propagating downward through the mantle transmit no measurable energy into the core, thus documenting the lack of any rigidity in the outer core at the frequencies of these seismic waves (0.1–1 Hz). By contrast, vertically polarized shear waves reaching the mantle–core boundary generate a longitudinal (compressional) wave in the core that can then generate both a longitudinal and a vertically polarized shear wave when emerging back into the mantle on the far side of the core. The resulting waves are recorded at the Earth's surface.

The second, complementary line of evidence comes from the spectrum of the Earth's free oscillations excited by large earthquakes. The observed fundamental and overtone frequencies can only be explained by assuming that the outer core has zero rigidity. Although modeling the free-oscillation spectrum is by itself an inverse problem with no unique solution, enough additional information is available from body-wave seismology and other geophysical observations to show reliably that the outer core is fluid.

Finally, geodetic observations of the nutation spectrum (wobble of the Earth's rotation axis) are best fitted by assuming that the outer core is a fluid no more viscous than water at room temperature and pressure. The recent observations of inner-core rotation are compatible with such low viscosity, implying that electromagnetic rather than viscous forces dominate the coupling between the fluid outer core and the crystalline inner core.

- **The inner core is crystalline.** The only direct evidence that the inner core is *not* fluid comes from the observed spectrum of seismic free oscillations, which cannot be fitted unless the inner core is assumed to have a finite rigidity. Fitting the free-oscillation spectrum also shows that the inner core is about 0.5 g/cm^3 denser than the outer core. Furthermore, the anisotropy of elastic-wave velocities argues for a crystalline inner core.

No shear wave propagating through the inner core has ever been convincingly observed to date, and calculations based on the known structure of the Earth indicate that the amplitudes of such waves are far too small to be observed at present. It is possible, however, that future measurements, including observations at the antipode of an earthquake, may reveal evidence for such waves.

- **The geomagnetic field comes from the core.** A spherical-harmonic fit to the time-averaged geomagnetic field on and above the Earth's surface proves that over 98% of the field at the surface is due to sources deep inside the planet. That was

continued on next page

already known in the 19th century through one of Gauss's early applications of spherical harmonics. Geomagnetic storms caused by rapid changes in solar-wind activity occasionally increase the external geomagnetic field, temporarily reducing the contribution from the interior to only about 90%.

Temporal variations, over years or decades, of the geomagnetic field and electric currents measured in the crust show that the bulk of the mantle has low electrical conductivity. That finding is compatible with seismological and other evidence that the mantle consists primarily of electrically insulating silicate and oxide rock. By contrast, the seismological properties of the core are compatible with nearly pure iron, indicating that the geomagnetic field is primarily produced by magnetohydrodynamic processes in the electrically conducting fluid of the outer core.

Because the bulk of the mantle is insulating, only the radial component of the core's magnetic field is observed at the surface; the tangential component is not propagated through the mantle. That only one of the two components of the geomagnetic field is directly observed is especially problematic, because of theoretical expectations that the unobserved tangential field in the core is at least as strong as the observed radial field.

Measurements of the time-varying geomagnetic field over periods of decades to centuries can be used to infer the fluid velocity at the top of the outer core. Global observations of this time variation go back several centuries. They yield flow velocities of about 1–10 km/yr at the top of the outer core. For comparison, flow velocities in the "solid" regions of the Earth—the mantle, the inner core and the surface tectonic plates—are measured in centimeters per year.

► **The core is an iron-rich alloy.** Laboratory measurements show that the densities and elastic-wave velocities of elements and planetary materials vary rather systematically with atomic mass (mean atomic weight, in the case of compounds). Thus seismological measurements of density and elastic-wave velocities tell us that the average atomic number of the core is about 25, close to that of iron.

The only known mechanism that can produce the geomagnetic field is magnetohydrodynamics, which requires the presence of an electrically conducting fluid. Only a metallic liquid, such as molten iron alloy, can be involved at these pressures and densities. (In other, more diaphanous contexts, plasmas are important sources of magnetohydrodynamic fields.)

Iron is thought to predominate in the core because it is orders of magnitude more abundant in the Solar System than neighboring elements in the periodic table. This abundance is well understood in terms of stellar nucleosynthesis. It's implausible that very rare elements, such as vanadium or chromium, would make up a large part of our planet.

There's also the evidence from meteorites. Most of them are rocky, but about one in ten is metallic, and the metallic ones turn out to be iron–nickel alloy. Because meteorites are thought to be samples of the materials left over from planet formation, it seems most reasonable that the core is an iron-rich alloy.

We know, however, that the core is not entirely pure iron or iron–nickel alloy. Comparing the seismological observations with high-pressure measurements of equations of state reveals that the core is about 10% less dense than pure Fe (or Fe–Ni) at the pressures and temperatures of the core. The identification of the lighter contaminant is highly controversial. Among the current favorites are sulfur, oxygen and hydrogen. All of these can satisfy the physical observations of the Earth's interior, and preferences relate mainly to particular models of the origin and earliest geological history

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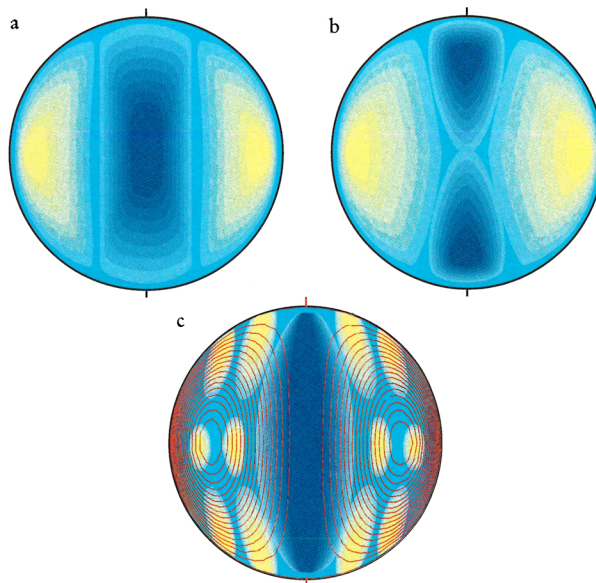


FIGURE 2. CROSS SECTIONS OF THE INNER CORE, with the rotation axis vertical, exhibit variations of calculated longitudinal seismic-wave velocities for propagation parallel to the rotation axis. Highest velocities are shown in dark blue; lowest in yellow. **a** and **b** are simply axially symmetric fits to 19- and 16-mode seismological data sets, respectively. These observational results are in reasonable agreement with **c**, which shows the predictions from a model of solid-state convection throughout the inner core. Flow lines for the lowest-order convection mode are shown in red. (Adapted from ref. 4, Romanowicz *et al.*)

examined by two different groups, led to the same basic conclusion about the rotation of the Earth's inner core.

Meteorology of the liquid core

In this way, seismological observations can monitor the motions at the bottom of the outer core on time scales of years. Thus they provide us with new insights into the "meteorology" across the full depth of the fluid outer core, where the geomagnetic field is created. That complements the estimates of motions at the very top of the outer core derived from analyzing the time variations of the magnetic field at the Earth's surface. (See the box.)

Dynamical scaling arguments tell us that annual determinations of fluid-core motions, which are now possible, are equivalent to hourly observations in conventional atmospheric meteorology. The timing of the fluid-core observations is closely linked to major advances in the theoretical understanding of core dynamics. In particular, Glatzmaier and Roberts have carried out unprecedented numerical simulations of the magnetohydrodynamic dynamo process that creates the geomagnetic field.^{1,2} (See figure 3 and PHYSICS TODAY, January 1996, page 17.) One of their first successes was in finding that their model calculation seems to generate a magnetic-field reversal after about 3×10^4 years.¹ In more recent work, not yet published, Glatzmaier and Roberts found subsequent model-generated reversals roughly 120 000 and 220 000 years after the first. In the real world, the Earth's magnetic field is known to reverse its polarity typically a few times every million years.

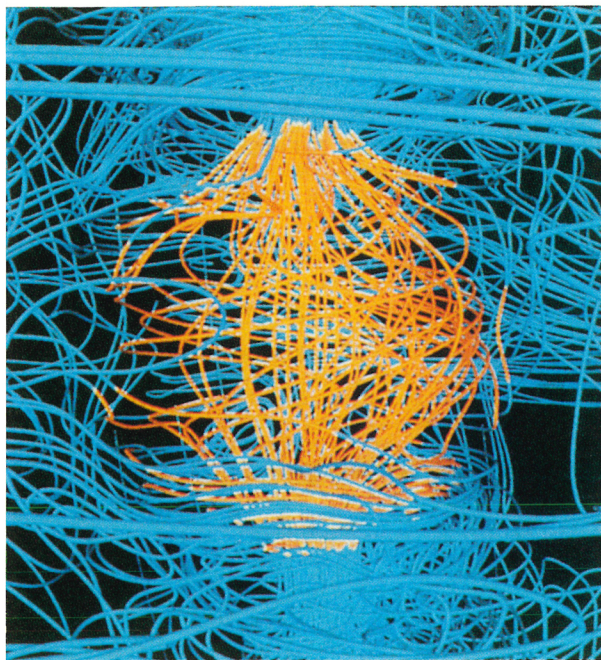
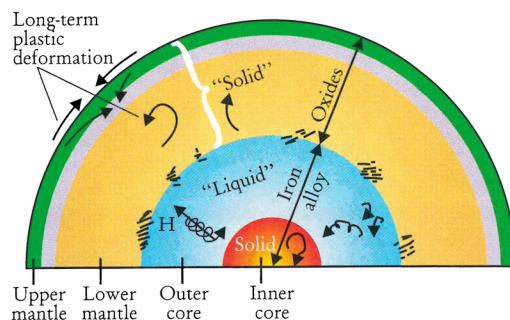


FIGURE 3. SIMULATED MAGNETIC FIELD LINES in the Earth's liquid outer core are swept by fluid motions, thus helping to induce the superrotation of the solid inner core. The figure is from ref. 2, which describes the model. Field lines shown in blue (gold) are outside (inside) the inner core. The rotation axis is vertical. Maximum magnetic field is about 300 gauss.

A curious outcome of the magnetohydrodynamic calculations is that the inner core appears to rotate faster than the Earth's mantle. (See *PHYSICS TODAY*, September 1996, page 17.) The cause of this inner-core "superrotation," if it is really happening, is complex in detail. That's because the fluid-flow and magnetic fields of the outer core are intimately linked. Still, one effect of the Earth's rotation is that outer-core fluid is spun up as it descends from the mantle toward the polar caps of the inner core.^{2,9} Magnetic field lines in the liquid metal of the outer core thus tend to be dragged forward and, because these field lines also thread through the metallic inner core, the result is a superrotation calculated to be about 2–3 degrees per year.²

This calculated magnetohydrodynamic result is in excellent agreement with the observations. Indeed, the prediction was made prior to the seismological work.^{1,7} More significantly, it is one of the first times that geomagnetic dynamo simulations of processes deep inside the core could be directly checked against independent observations. Given the major assumptions built into the theory—for example, in the treatment of outer-core turbulence—the evident agreement between theory and observation provides a new level of confidence in the modeling. A further prediction of the model is that the inner-core motion should be somewhat jerky, at least on time scales of centuries and perhaps even on shorter periods that can be checked against seismological and geomagnetic observations over the coming years.

To the extent that the computer simulations are realistic, they offer a hope of revealing key aspects of the core's long-term geological evolution. For example, the



CROSS SECTION THROUGH THE EARTH shows a metallic core enclosed by a rocky outer shell. Turbulent convection in the liquid outer core creates the geomagnetic field H . All of the interior is in motion. Heterogeneous lumps of material accumulate at the highly reactive core-mantle boundary. The distinction between "solid" (mostly crystalline) and "liquid" (mostly molten) is primarily a difference of motional time scales: centimeters per year instead of per minute.

of the core. For example, oxygen and hydrogen alloy with iron only at high pressures, so that they could have become significant contaminants only if they infiltrated the core metal after the Earth had grown to a large fraction of its present size, with the core at the center. If the laboratory experiments and geophysical observations are really telling us that the mantle and core are reacting chemically, then the core has been getting increasingly contaminated by oxygen over geological time.

► **The core temperature is about 5000 K.** The temperature at the boundary between the crystalline inner core and the fluid outer core is evidently close to the melting temperature of the core material at the appropriate pressure. The density profile through the Earth, obtained by inverting the free-oscillation spectrum (and including gravity among the restoring forces), gives the radial variation of density, and hence pressure, through the interior. This exercise yields a pressure of 3.6×10^6 atmospheres at the center of the solid inner core, falling to 1.4×10^6 atmospheres at the top of the liquid outer core.

Laboratory experiments at high pressures and temperatures reveal that iron and plausible iron alloys melt at about 4000–6000 K at core pressures. Although the quantitative details are still controversial, with notable discrepancies between different laboratories and different methods (sometimes between different methods in the same laboratory!), the consensus is that temperatures are between 3500–4500 K at the top of the core and go up to 5000–6000 K at the center of the Earth. Ultimately, the main source of uncertainty for temperatures in the core derives from our uncertainty as to its composition.

Glatzmaier–Roberts model that best fits the observed inner-core motions involves a greater loss of heat from the core to the mantle than one would conclude from most of the recent studies of the Earth's thermal history.² That is important, because heat flow from the core into the mantle helps drive plate tectonics, volcanism, earthquakes and other geological processes of the Earth's crust. This

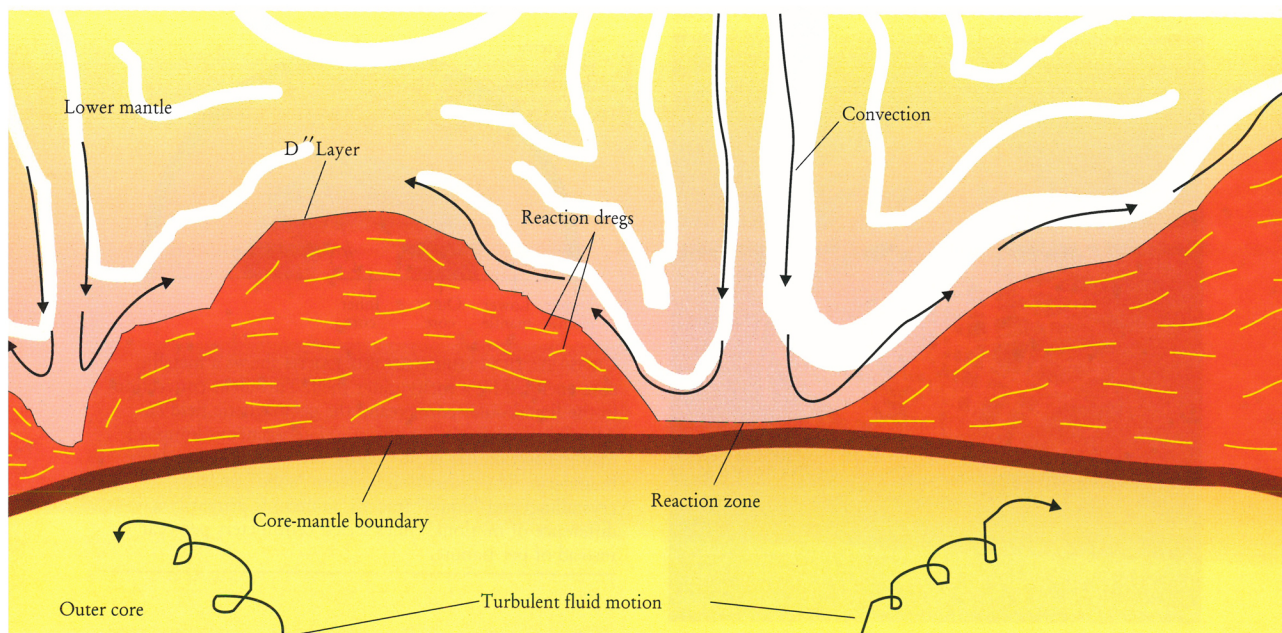


FIGURE 4. CROSS SECTION OF THE CORE-MANTLE BOUNDARY region, schematically illustrating complex chemical and physical interactions where the mantle's rock meets the outer core's liquid metal. The mantle undergoes slow plastic deformation, yielding convection velocities of centimeters per year, while the outer core has turbulent fluid flows of centimeters per minute. Heterogeneous materials are swept up to form the lumpy D'' layer (shown red). Alignment of reaction dregs and thin molten zones within this layer may be responsible for the anisotropies in seismic-wave velocities. (Adapted from ref. 10, Jeanloz and Lay.)

greater heat flow across the core-mantle boundary implies that the core modulates the geological evolution of our planet more strongly than had been previously appreciated.

Core-mantle interactions

There is increasing evidence that the Earth's metallic core does indeed interact very strongly with its surrounding rocky (or ceramic) mantle.¹⁰ Seismology, for example, reveals that the lowermost 200 km of the mantle is one of the most heterogeneous regions of the planet: Scattering and other phenomena associated with strong lateral variations in physical properties make this region somewhat turbid to geophysical observations. We also know from laboratory experiments that the oxides of the Earth's deep mantle react vigorously when placed in contact with liquid iron alloys at the high pressures and temperatures of the core-mantle boundary. These experiments suggest that the rocky mantle is slowly dissolving, over geological time spans, into the liquid metal of the outer core.

The reason for this slow dissolution seems to be related to a fundamental change in the bonding character of oxygen at high pressures. Whereas oxygen forms insulating compounds (typically ceramics) at low pressures, it can become a metal-alloying component at high pressures. The insulator-metal transition is complex in detail, as exemplified by the transition-metal oxides.¹¹ Thus, in combination with the seismological observations, high-pressure experimental and theoretical investigations point to the core-mantle boundary as being perhaps the most chemically active region of the Earth's interior.

The products of chemical reactions between these two regions—where insulating oxides meet metallic alloys—might well explain the seismologically observed heteroge-

neity near the core-mantle boundary.¹⁰ (See figure 4.) In addition, piles of "dead slabs"—oceanic crust that has settled toward the bottom of the mantle—may contribute further to the heterogeneity of the region.¹² (See the discussion of mantle convection in the news story on page 17 of this issue.)

The possible occurrence of varying amounts of metal alloys at the base of the mantle is especially important, because metal conducts heat much more readily than do the insulating oxides. Therefore, heat may be emerging from the top of the core in a spatially variable manner that can determine the pattern of solid-state convection throughout the Earth's mantle.¹³

Patches on the mantle's bottom

Perhaps the most unusual anomalies seen near the core-mantle boundary are thin patches, less than 40 km thick, in which the seismic-wave velocities are locally reduced by 10% or more.¹⁴ Such ultralow-velocity zones are not seen anywhere else in the bulk of the mantle. Even if we assume chemical reaction with (or contamination by) the underlying core, it would seem that explaining these very reduced seismic velocities also requires massive local melting within the lowermost mantle.

Such blatant heterogeneity, with locally hot and partially molten zones in the lowermost mantle, is but one manifestation of the highly dynamic thermal and chemical boundary layer at the outermost surface of the Earth's core. It has been suggested that "plumes" at the Earth's surface—groups of volcanoes (such as the Hawaiian island chain) thought to represent upwelling jets of hot rock in the mantle—may be preferentially lined up above the ultralow-velocity molten patches just above the core-man-

tle boundary.¹⁵

Better yet, there is good evidence of locally strong seismic anisotropy just above the core.^{16,17} Although its relation to the ultralow-velocity zones is yet to be determined, the anisotropy does vary from one location to another, with horizontally polarized shear waves propagating a few percent faster or slower than vertically polarized waves. The presence of thin layers of material with slow acoustic velocity, whether from partial melting or contamination by the core (or both), could explain the anisotropies at the base of the mantle. One could imagine that such layers are streaked horizontally by the background flow of rock at the base of the mantle. However, the most recent observations of anisotropy also suggest the occasional presence of vertical streaking, which is what would be expected where fluid-dynamical instabilities due to heat from the core trigger plumes of hot rock "jetting" upward toward the surface in tens of millions of years. By geological standards, that's pretty fast.

We have seen that seismological observations of the core-mantle boundary region document the combined thermal and chemical influence of the metallic core on the rocky mantle. That could be important for understanding past geological phenomena of enormous magnitude. In particular, there is evidence for periods of massive volcanic eruptions at localized rates hundreds of times as great as anything the Earth has experienced in recent geological—let alone human—history.¹⁸ Modeling studies suggest that such "superplume" events could be the surface manifestation of fluid-dynamical instabilities triggered from the core-mantle boundary. If so, current observations of seismic heterogeneity and anisotropy just above the core may be giving us the first glimpses of how such massive instabilities are initiated deep inside the Earth.

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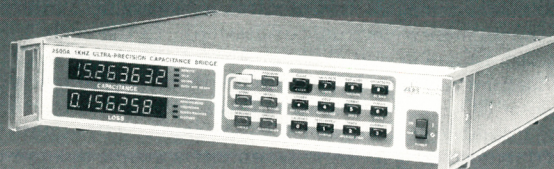
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