SCIENTIFIC AMERICAN
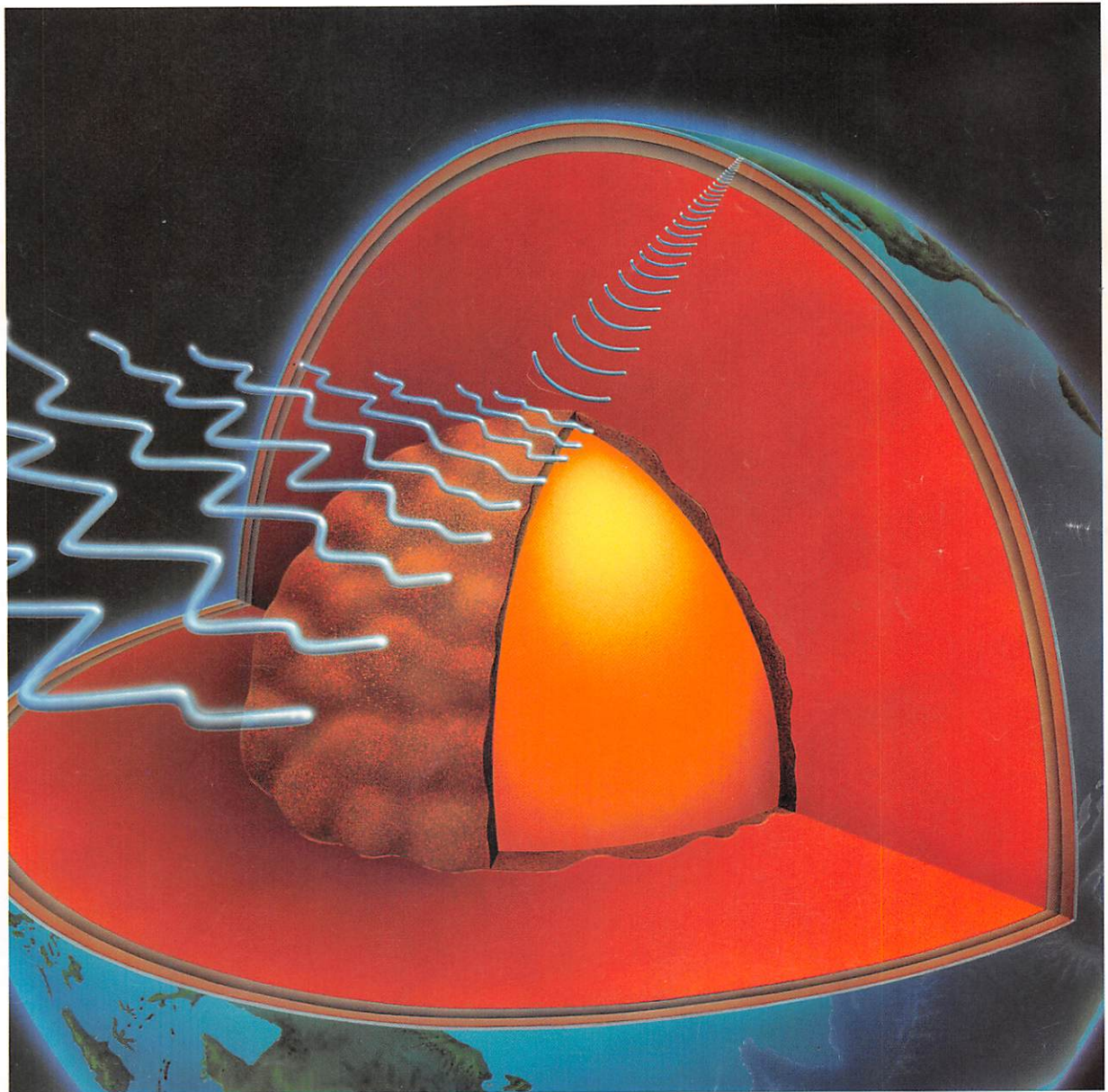
Building soft machines from smart gels.

The neurological pathways of fear.
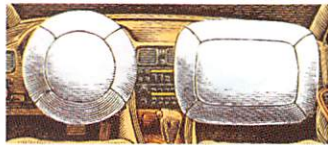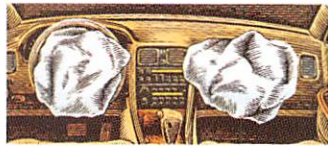
Life and death as economic indicators.

Seismic waves *trace the turbulent boundary between the earth's rocky mantle and molten core.*
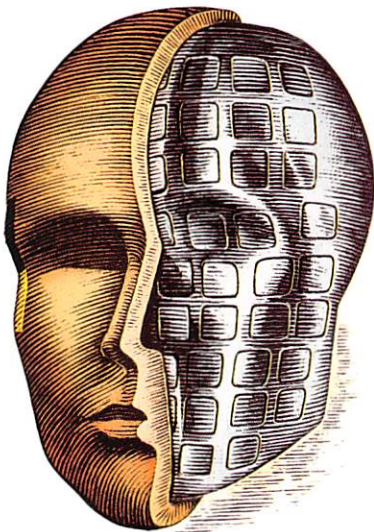
Conduct Your

1. Tear along the dotted line. *To see the real beauty of our California Walnut trim, break it into a few pieces. It's specially designed to resist splintering. Which, in an accident, is quite a luxury to have.*

2. Which is faster? *If accidents can occur in the blink of an eye, it's good to know our new dual airbags will have plenty of time to safely deploy.**

4. Press this.
How obsessed are we with safety? In future tests we'll be using crash dummies equipped with 54 facial sensors that can measure the impact of a fingerprint or something much more substantial.

Lexus engineers spent years developing the safety features of the 1993 LS 400. But you'll

The Core-Mantle Boundary

*This interactive zone may be the most
dynamic part of the planet, directly affecting
the earth's rotation and magnetic field*

by Raymond Jeanloz and Thorne Lay

About 2,900 kilometers away—less than three days' drive, if that were possible—lies the most dramatic structure of the earth. Largely ignored in past research, the remote region between the lowermost mantle and the upper core is proving to be crucial in understanding the chemical and thermal evolution of the planet. No longer regarded as simply a contact delineating the liquid-iron outer core from the rocky mantle, the core-mantle region may actually be the most geologically active zone of the earth. Its features seem to have changed immensely during the earth's history, and its physical properties now evident vary from place to place near the bottom surface of the mantle. In fact, the physical changes across the interface between the core and mantle are more pronounced than are those across the planetary surface separating air and rock.

The strong heterogeneity of the core-mantle boundary region is thought to influence many global-scale geologic processes [see "The Earth's Mantle," by D. P. McKenzie; SCIENTIFIC AMERICAN, September 1983]. The dynamics of the zone affect the slight wobbling of the earth's axis of rotation and characteristics of the geomagnetic field. Variations in the core-mantle region also modu-

RAYMOND JEANLOZ and THORNE LAY study the physics of the deep earth. Jeanloz, professor of geology and geophysics at the University of California, Berkeley, received his Ph.D. in 1979 from the California Institute of Technology. A MacArthur Fellow, Jeanloz also studies the internal evolution of other terrestrial planets and the formation of new types of glass that have novel properties. Lay is professor of earth sciences at the University of California, Santa Cruz, where he is also director of the Institute of Tectonics. His specialty is the study of earthquakes and the structure of the earth's interior. A recipient of the American Geophysical Union's 1991 Macelwane Medal, Lay earned his Ph.D. in 1983 from Caltech.

late the convection in the earth's mantle, which is responsible for the movement of continents and tectonic plates.

The first hint that something unusual was going on at the depth where the core and mantle meet came in the mid-1930s. Vibrations generated by earthquakes provided the clue. Throughout most of the mantle, the speed of seismic waves increases as a function of depth. Furthermore, lateral variations in seismic-wave velocity are only minor. One can interpret these characteristics as meaning that the earth gets "simpler" with respect to depth, that is, the composition and structure of the planet become more uniform. In contrast, the great diversity of geologic structures and rocks observed underfoot reveal the surface to be the most complicated region.

Yet the velocity behavior of seismic waves holds only to a certain point. At the lowermost few hundred kilometers of the mantle, just before the core begins, the average speed of seismic waves does not increase appreciably, and more meaningful changes in velocity appear from region to region [*see illustration on pages 50 and 51*]. The effect is subtle, amounting to only a few percent difference. Yet by geologic standards, these few percent represent enormous variations in structure or temperature, or both. Early workers recognized the significance of the changes from the simple behavior in the overlying lower mantle and consequently named this region, which was deduced to be about 200 to 400 kilometers thick, the D″ layer.
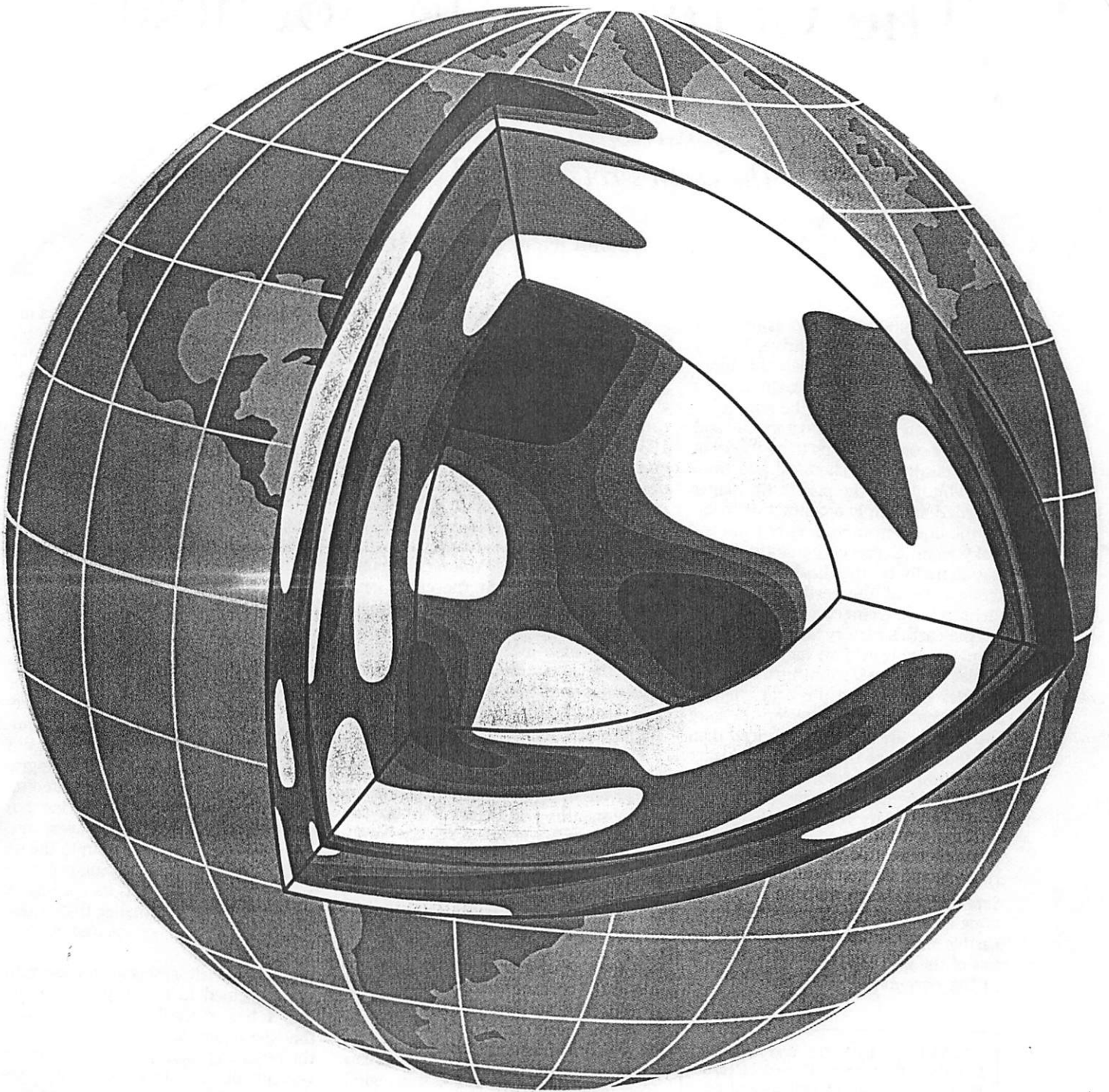
The origin of the layer's name (pronounced "dee double prime") is more historic than poetic. Early geologists had labeled the parts of the deep earth with letters of the alphabet, rather than as crust, mantle and core. This form of identification, however, meant that any intervening layer subsequently discovered had to incorporate a "prime" symbol to distinguish it. Although other layers were eventually renamed, the D″ nomenclature has endured.

Investigators proposed numerous interpretations to account for the seismic properties of the D″ layer. Unfortunately, there were too many possible explanations and too little information to permit a definitive characterization of the layer. Better descriptions of the D″ layer had to wait until the technological breakthroughs of the 1980s. Then, using arrays of recording instruments deployed around the world, seismologists could for the first time collect and process enough data to derive three-dimensional images of the earth's interior [see "Seismic Tomography," by Don L. Anderson and Adam M. Dziewonski; SCIENTIFIC AMERICAN, October 1984]. The seismometers used primarily operate in the range between about one and 0.0003 hertz, or cycles per second. (These acoustic frequencies are far below the range of human hearing, which extends from about 20 to 20,000 hertz.) Seismic tomography is often compared to computed tomographic scans used in medicine. But because it relies on sound waves, seismic tomography is more akin to the ultrasonic imaging done during pregnancy. The main drawback is its resolution: images of features smaller than 2,000 kilometers tend to be smeared out.

Nevertheless, seismic tomography helped to quantify the properties of the D″ layer. It showed that the region differs drastically from the overlying mantle. The fact that the velocity of seismic waves is affected over continent-size areas shows that large-scale structures dominate D″. Still, seismic tomography could not explain the causes of this variability in physical properties. Could large, chemically distinct structures exist at the bottom of the mantle, just as continents mark the seismic heterogeneity of the earth's surface? Or are the heterogeneities simply large-scale temperature differences at the base of the mantle?

To answer these questions, one of us (Lay) began in the early 1980s to implement a new method to explore the core-

SEISMIC-WAVE VELOCITIES differ throughout the earth's interior, as depicted in this image generated by seismic tomography. In some regions the waves move more quickly than is average for that depth *(blues)*; in others the waves are slower *(yellows)*. Such variations can suggest differences in composition. Much of the complexity of the core-mantle boundary (the exposed surface of the outer core) is not evident, because the heterogeneities are too small to be resolved.

[handwritten: white]
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mantle boundary. The idea was to use computer calculations to analyze all the characteristics of the observed seismic wave front, not just the wave velocity, as in the case of tomography. Such waveform analysis is a powerful approach because the technique can resolve structures as small as a few tens of kilometers across instead of those 2,000 kilo-

meters or more in size. The disadvantage is that one can look only at limited parts of the core-mantle boundary. There are not enough earthquakes or other sources of seismic energy to obtain a global picture at such a high level of detail.

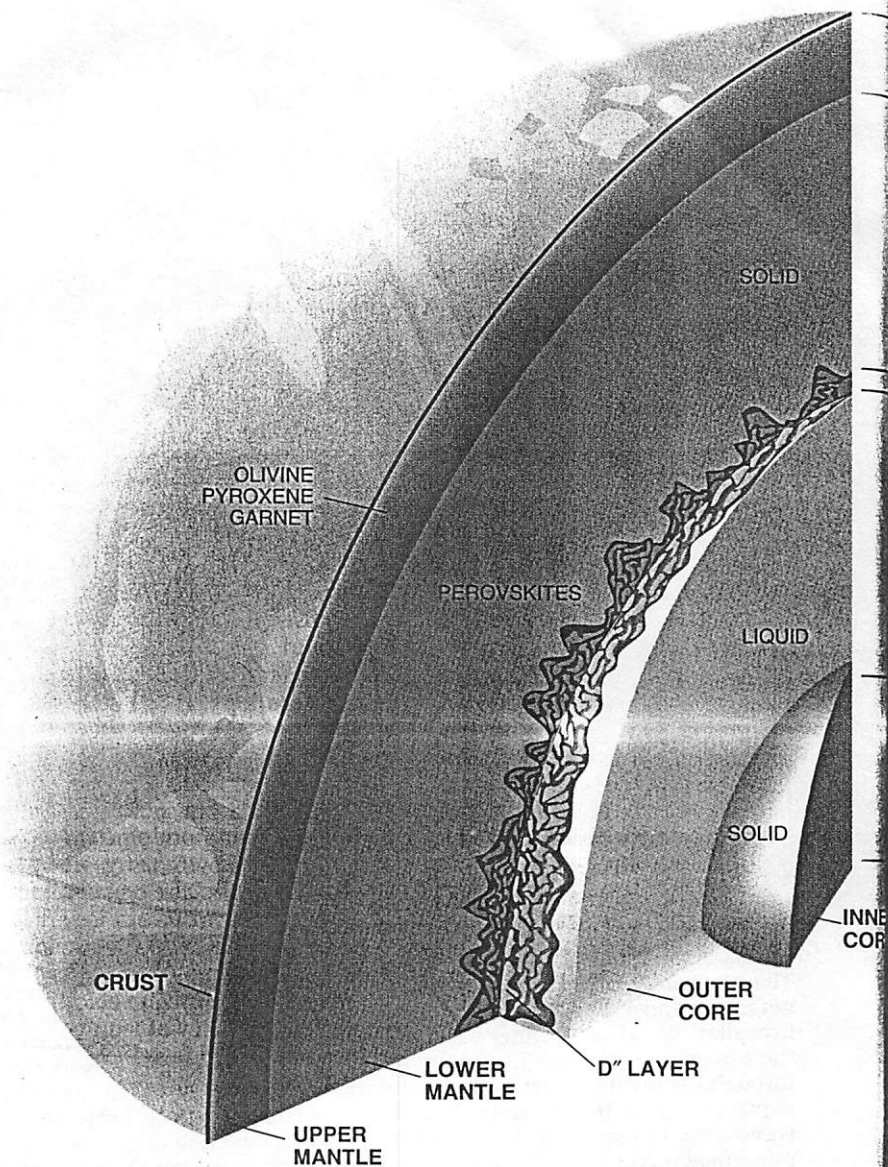The waveform studies suggest that neighboring regions within the D″ lay-

er can be more distinct than had once been thought. For example, several research groups studying the core-mantle boundary below northern Siberia found that acoustic velocities vary so radically over short distances that closely spaced seismometers systematically recorded different waveforms. The finding can best be explained by assuming that the

heterogeneity in seismic velocities is large in magnitude and occurs over distances smaller than can be resolved, that is, within a few tens of kilometers. Waveform studies can also map the differences in thickness of the D″ layer. In many places the top of the D″ layer causes an abrupt increase in wave velocity, a process that reflects seismic energy. The reflections have revealed that the thickness of the D″ layer varies dramatically. The layer can be so thin as to be undetectable, or it can span as many as 300 kilometers.

Stanley M. Flatté's group at the University of California at Santa Cruz helped to confirm the great variability of the D″ layer. During the mid- to late 1980s, he and his colleagues began to apply new methods of wave analysis to the signals obtained from seismic waves that have been scattered in the deep mantle. Their method relies on a statistical description of how waves propagate through a strongly scattering substance. Such material would be analogous to fog or clouds. Flatté's approach is to observe how the wave front from an earthquake changes shape after traveling through the D″ region. An earthquake initially sends out a smooth, spherically expanding wave. But as that wave is refracted and scattered by variations in seismic features, such as the strong heterogeneities near the core-mantle boundary, the front no longer remains smooth. It becomes rippled, or corrugated [*see illustration on page 53*].

The trick in measuring the degree of wave-front corrugation is a dense array of seismometers. Taking observations from one such collection located in Norway, Flatté has shown that the D″ region appears quite murky to seismic waves. It must contain heterogeneous features as small as 10 kilometers in length. The seismological observations thus indicate that the D″ region is a heterogeneous layer that laterally varies in thickness.

In contrast to the murkiness of the D″ layer, the core-mantle boundary (on which the D″ layer rests) appears smooth and sharp. Last year John E. Vidale and Harley Benz of the U.S. Geological Survey beautifully demonstrated the abruptness of the interface. They used a vast number of seismic recording stations that had been deployed across the western U.S. The array of seismometers generally monitors regional earthquake activity, but Vidale and Benz have employed it to find seismic waves that have bounced off the core-mantle boundary. Remarkably, seismic waves arrived coherently across more than 900 stations in the array. This coherence implies that the core-mantle boundary

SOLID

OLIVINE PYROXENE GARNET

PEROVSKITES

LIQUID

SOLID

CRUST

INNER CORE

OUTER CORE
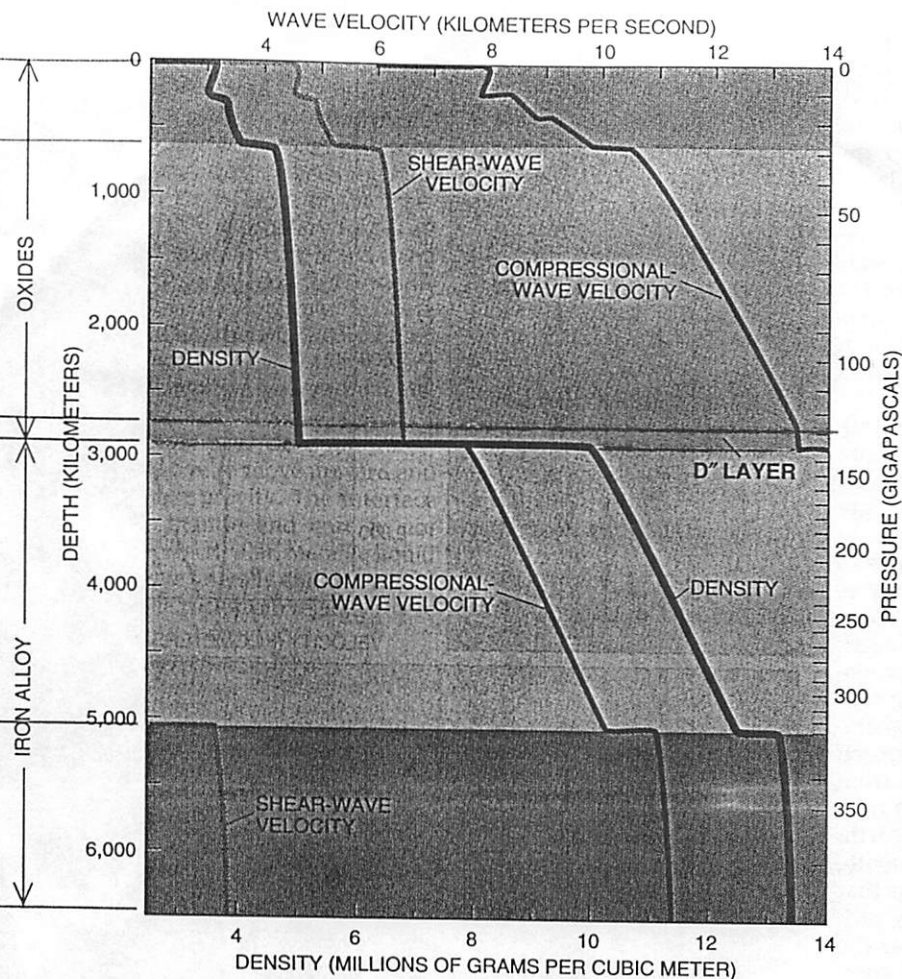
D″ LAYER

LOWER MANTLE

UPPER MANTLE

represents a sharp transition from the mantle to the core, at least for the area measured. The sudden transition reflects as much as 50 percent of the seismic waves and transmits the remainder. Analyses of the reflected and transmitted waves show that the boundary varies in depth by no more than a few kilometers.

Seismic-wave studies have done much to elucidate the D″ layer and the core-mantle boundary. But the inaccessibility of the regions has prevented geophysicists from understanding completely how such complicated structures came about.

If seismic studies cannot thoroughly breach the remoteness of the deep earth, why not bring the core and mantle to the surface? That is precisely the approach taken by many research-ers, including one of us (Jeanloz). Specifically, we sought to duplicate the high pressure and temperature existing in the deep mantle and core. A breakthrough in engineering made such a feat possible: investigators had learned to compress minuscule samples between the points of two diamonds and to heat the specimen using a high-powered laser beam [see "The Diamond-Anvil High-Pressure Cell," by A. Jayaraman; SCIENTIFIC AMERICAN, April 1984]. By 1986 the diamond cells could generate pressures greater than those at the center of the earth.

Diamond's hardness is not the only reason for using the substance as an anvil. The utility of diamond also lies in its transparency. A laser beam can be focused directly through the diamond to heat the sample to thousands of degrees Celsius. Moreover, one can ob-

WAVE VELOCITY (KILOMETERS PER SECOND)

SHEAR-WAVE VELOCITY

COMPRESSIONAL-WAVE VELOCITY

DENSITY

OXIDES

DEPTH (KILOMETERS)

COMPRESSIONAL-WAVE VELOCITY

DENSITY

D" LAYER

PRESSURE (GIGAPASCALS)

IRON ALLOY

SHEAR-WAVE VELOCITY

DENSITY (MILLIONS OF GRAMS PER CUBIC METER)

CROSS SECTION OF EARTH shows the planet's primary regions (*opposite page*). The crust and mantle consist of oxide crystals such as olivine, pyroxene and garnet in the upper mantle and silicate perovskite in the lower mantle. The core is an iron alloy, liquid in the outer part and solid in the center. The layers correspond to the observed variations in density and velocity of seismic waves as they travel through the earth (*above*). Both density and wave velocity increase as a function of depth except at the D" layer. Note that seismic energy can propagate as shear waves (waves that oscillate at right angles to the direction of motion) and as compressional waves (waves that move back and forth in the travel direction). Because liquids do not have rigidity, shear waves cannot propagate in the outer core. Shear-wave motions reappear in the inner core because a fraction of the compressional waves transforms into shear waves at the liquid-solid interface.

serve the specimen while it is at super-high pressures and temperatures. One determines the temperature of the sample by measuring the thermal radiation the sample emits through the diamond. In this way, one can quantify how "red hot" or "white hot" the material has become; astronomers infer the surface temperatures of stars by color in the same manner. Using the laser-heated diamond cell, we can simulate the appropriate temperatures and pressures at the core-mantle boundary. We wanted to see what would happen when we placed matter that constitutes the outer core in contact with minerals of the lowermost mantle.

Of course, we needed to know what materials make up the mantle and core before squeezing them together. To determine the mantle constituents, Elise Knittle, working with Jeanloz, followed up on research by groups at the Australian National University, the Carnegie Institution of Washington and elsewhere. We relied on prior experimental work, on theoretical models and on the fact that the pressure in the lower mantle exceeds 20 gigapascals (200,000 atmospheres).

From that information, we deduced that a single high-pressure mineral phase must dominate the lowermost mantle. This mineral is a dense form of iron magnesium silicate, or $(Mg,Fe)SiO_3$, a robust and chemically simple compound that can be formed only under pressures above 20 gigapascals. Because it has the same crystalline structure as the mineral perovskite ($CaTiO_3$), it is consequently called magnesium silicate perovskite. The lower mantle rock probably also contains minor amounts of magnesiowüstite—a combination of magnesium oxide (MgO) and wüstite (FeO). This composition is quite unlike the nature of rocks at or near the earth's surface. Such rocks are composed of many different, complex minerals that react chemically and transform into new minerals under modest changes of pressure or temperature. The deduced chemical simplicity of the deep mantle accords well with the data derived from seismic waves, which show it to be relatively devoid of structure (except for the D" layer). This consistency gives us confidence that we are examining the appropriate minerals in our laboratory simulations.

Determining the constituent of the core was more straightforward. Seismological studies done more than 50 years ago enabled geophysicists to infer its structure. The core consists of a molten substance surrounding a solid center. The fluid is acknowledged to be a metal—specifically, an alloy of iron. In fact, the churning of the molten iron generates the earth's magnetic field.

Having established the compounds involved, Knittle carried out a series of experiments in which liquid iron was put in contact with crystalline silicate perovskite at high pressures. She found that the perovskite reacts vigorously with liquid iron, even if these substances touch for just a few seconds. The nature of the chemical reaction is quite interesting and unexpected. The products are a mixture of electrically insulating oxide minerals—magnesium silicate perovskite and stishovite (SiO2)—and metallic alloys—iron silicide (FeSi) plus wüstite. Wüstite had not been known to be able to form a metallic alloy at any temperature or pressure. Qualitatively speaking, wüstite can react this way because its oxygen atom at high pressures takes on the chemical attributes normally ascribed to its neighbor in the periodic table, sulfur. Metallic sulfides such as iron disulfide (pyrite, or fool's gold) are of course well known.

The experiments also showed that liquid iron begins to react with mantle substances at pressures of 20 to 30 gigapascals. Such pressures are far less than those at the core-mantle boundary (136 gigapascals). Therefore, the reactions have probably persisted since the earliest history of the planet—that
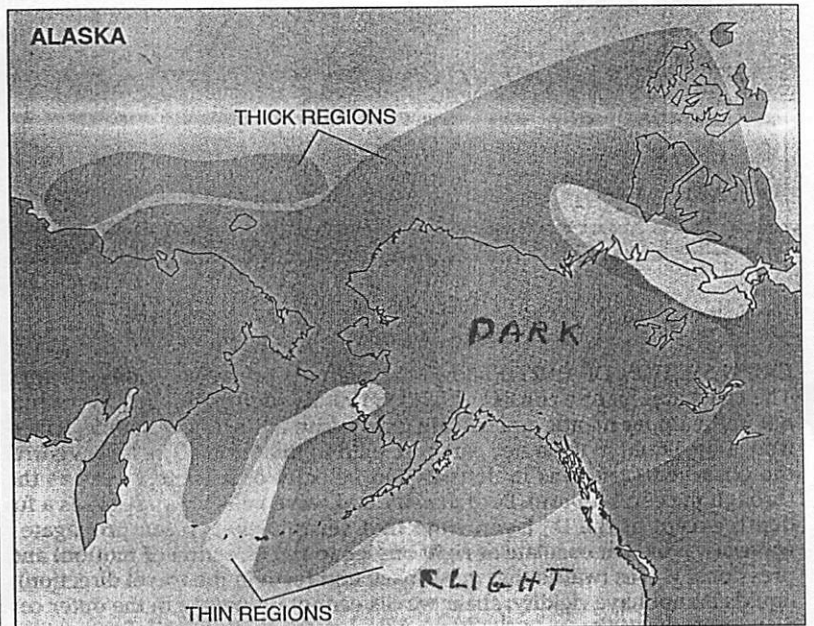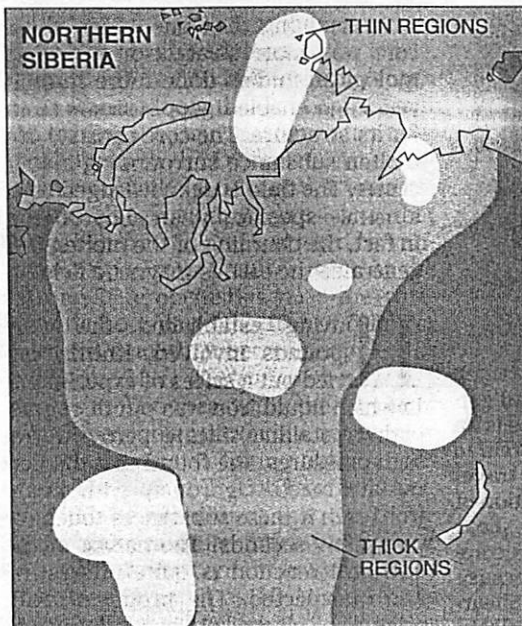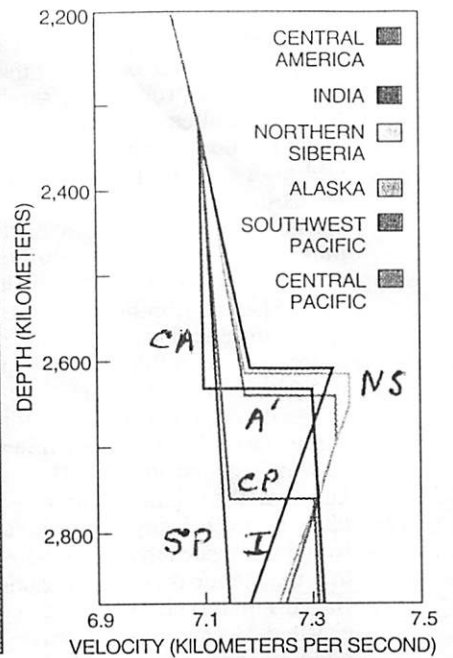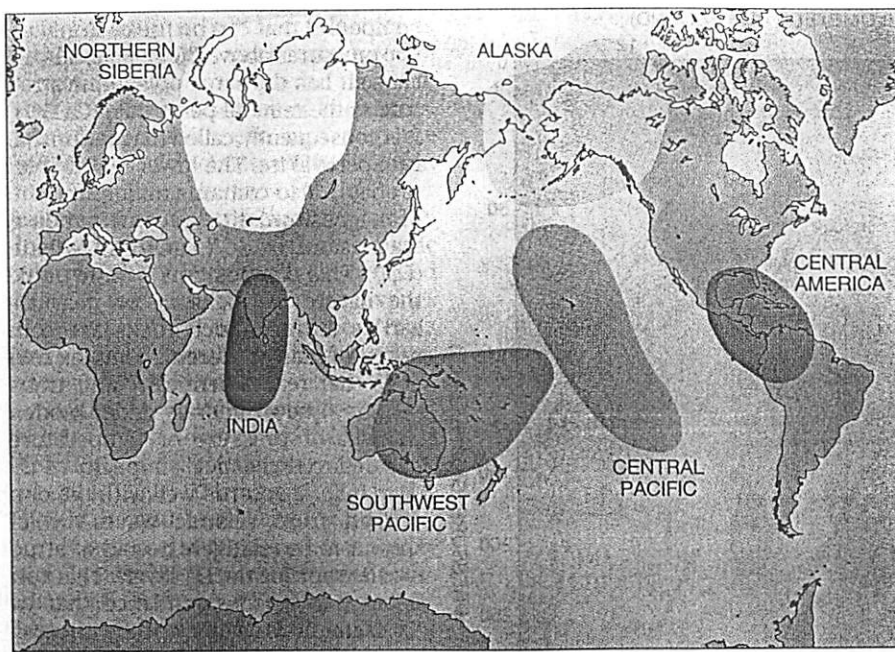
SHEAR-WAVE VELOCITY in the D″ layer changes across the earth, as indicated by the six regions (*colored areas, top left*) that have been most intensely studied. The corresponding velocity distribution as a function of depth (*top right*) shows that each region exhibits a discontinuity at the D″ layer. The uniqueness of each velocity signature implies that D″ varies over the entire globe. The expanded maps (*bottom*) for areas below northern Siberia and Alaska summarize the heterogeneity of D″, showing the intermingling of thick regions (*dark patches*) with parts so thin as to be seismically invisible (*light patches*).

is, when the earth was developing and the core might have been forming at pressures below 136 gigapascals. Such chemical reactions are likely to have significantly altered the core-mantle system. A considerable amount of oxygen has probably been drawn into, or alloyed with, the core metal over geologic history. In essence, the lower mantle rock has been and still is slowly dissolving into the liquid metal of the outer core. Berni J. Alder of Lawrence Livermore National Laboratory made this suggestion more than 25 years ago. Our

experiments substantiate his conjecture.

Indeed, one of the remarkable consequences of this hypothesis is that it offers a simple explanation for why the properties of the core are nearly but not exactly those of iron at the equivalent pressure and temperature. Most notably, the density of the outer core is about 10 percent lower than that of pure iron [see "The Earth's Core," by Raymond Jeanloz; SCIENTIFIC AMERICAN, September 1983]. But as indicated by Alder's hypothesis and our diamond-cell experiments, the core cannot

be completely iron. A purely iron core would have become tainted by reaction with the overlying rock over geologic time. Quite plausibly, the core was never pure iron. Instead it probably contained some nickel, sulfur and other minor constituents. Iron-rich meteorites provide the basis for this hypothesis. Such meteorites, considered partial remnants of the materials from which the earth formed, harbor many similar contaminants. Like pure iron, these iron-rich alloys can react chemically with rocky compounds at high pressures and tem-

peratures, forming an alloy with oxygen.

According to our experiments, the dense liquid of the outer core must seep into the rock, probably by capillary action. The molten metal would penetrate along the boundaries between the mineral grains at the bottom of the mantle. Estimates of the capillary forces involved suggest that the core liquid could move upward some tens to hundreds of meters above the core-mantle boundary. The reaction between core liquid and mantle rock probably takes place in less than a million years—instantaneously, in geologic terms.

The liquid, however, does not necessarily always have to move upward and to work against gravity. The interface between the mantle and core is not likely to be perfectly flat. Metallic liquid would permeate laterally and downward into the mantle rock from regions where the core-mantle boundary is elevated. Measurements from geodetic and seismological studies indicate that the topography of the core-mantle boundary deviates from absolute flatness by hundreds of meters to a few kilometers. Therefore, the zone of permeation and direct chemical reaction between the core liquid and mantle rock is no more than hundreds to at most thousands of meters thick. The size estimate explains why studies of seismic waves do not currently detect signs of reaction at the core-mantle boundary. The thickness of the reaction zone is less than typical seismic wavelengths. In addition, no more than a modest fraction of the reaction zone consists of liquid at any given moment. Thus, the presence of a small amount of liquid would not noticeably alter the velocity of seismic waves in the lowermost mantle.

How do these chemical reactions at the core-mantle boundary account for the observed characteristics of the D″ layer? The answer lies in a complex and indirect process resulting from forces that act on the core-mantle interface. The forces come from the thermal energy of the underlying core, which heats the rock at the base of the mantle. As a result, the heated part of the mantle moves upward over a period

of tens to hundreds of millions of years—far longer than the reaction between the core and mantle, which takes place in less than one million years. The convection must disrupt the reaction zone at the core-mantle boundary, entraining it upward and exposing fresh mantle rock to the corrosive liquid of the core. The convection is the same force that causes the tectonic plates to move at the earth's surface.

Mantle convection does not entrain liquids very far; any liquid metal that might be present in the boundary probably flows out, spongelike, through porous rock before moving upward. On the other hand, the iron-rich crystalline products from the reaction zone, such as wüstite, are readily incorporated into the mantle flow. The slow convection of the mantle pulls up the crystalline alloy a modest distance before the den-

sity of the metallic solids causes them to sink back toward the bottom. These solids essentially resemble the dregs of spice that remain at the bottom of a pot of mulled wine.

As a result, the alloy-rich substances would tend to pile up on the bottom of the mantle, especially near regions of upwelling, much as snowdrifts form in a blizzard. The upward dispersal abets infiltration of material from the core and builds a thicker zone of intermixing; the intermixing of reaction products and unreacted mantle causes the seismic heterogeneity. In contrast, downwelling regions would disperse the dregs and thus tend to thin the D″ layer and to depress the core-mantle boundary. Modeling by Louise Kellogg of the University of California at Davis and Norman H. Sleep of Stanford University and others suggests that the metallic alloys in local regions of the reaction zone may be swept upward several hundred kilometers into the mantle. The process would require tens of millions of years.

The buildup of the alloy-rich drifts at the bottom of the mantle solves an important mystery. Specifically, the drifts would explain the variation in thickness of the D″ layer observed by seismologists. Moreover, calculations indicate that the height of the alloy drift swept up in the mantle is comparable to the thickest parts of D″. Given the billions of years for progressive accumulation of the metallic dregs, it is plausible that much of the complexity and many of the variations in thickness of D″ result from the way mantle flow modulates the alloy-rich reaction layer. The flow may have also caught in its wake other dense mantle material or products from the core. We suspect that reaction dregs can collect, albeit to a lesser extent, on the inner side of the core-mantle boundary. A thinner version of the D″ layer probably exists there, just inside the liquid outer core.

In view of the intense dynamics taking place 2,900 kilometers below the earth's surface, it should not be surprising that the forces in the core-mantle system might be making their presence felt throughout the earth as a whole. Indeed, workers have

SEISMOMETER ARRAY
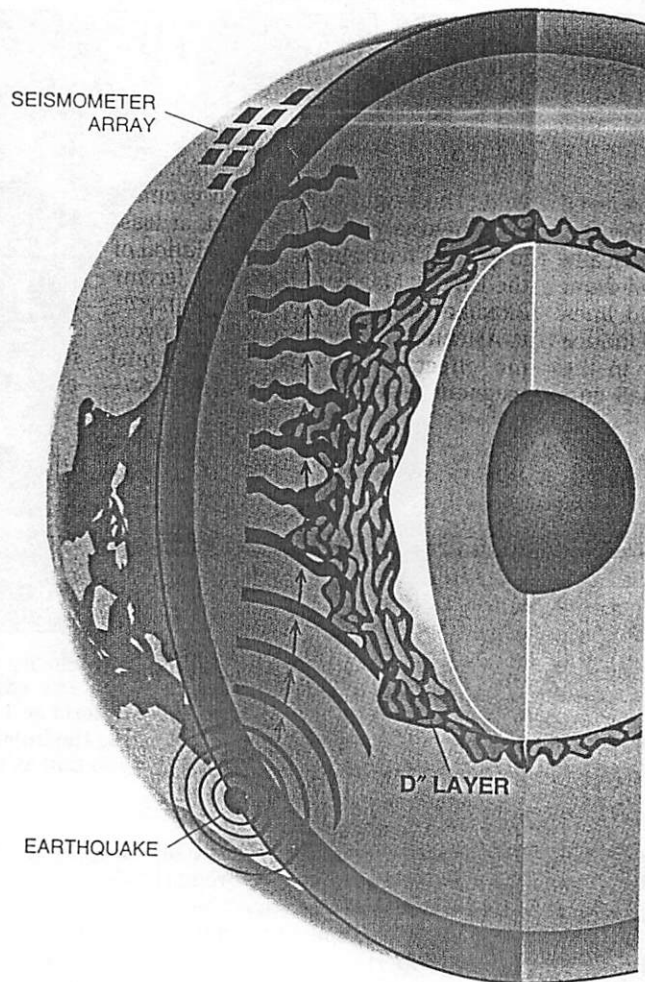
D″ LAYER

EARTHQUAKE

DISTORTION OF SEISMIC WAVES enables researchers to analyze the heterogeneous characteristics of the D″ layer. Waves emanating from an earthquake are smooth. When they pass through the D″ region, their wave fronts become rippled, or corrugated. The corrugation is measured by a dense array of seismometers located on another part of the earth. One such array, in Norway, was originally constructed to monitor seismic waves generated by underground nuclear tests.

found tantalizing evidence that suggests that the core-mantle zone strongly influences two features observable at the surface. They are the wobbling in the earth's rotation, known as nutations, and the geomagnetic field.

Bruce A. Buffett, working with Irwin I. Shapiro at Harvard University, concluded that the core-mantle boundary affects the earth's nutations. He did so after making highly accurate calculations of the wobbling. The workers measured the wobbling using very long baseline interferometry. Radio astronomers often rely on this technique to make highly precise measurements of stellar objects. Various tidal forces had been thought to be solely responsible for the earth's nutations. Such mechanisms include the friction generated as the solid surface of the earth rubs against the atmosphere and oceans as well as the gravitational interactions with the sun and the moon. Buffett discovered, however, a component of the nutations that could not be explained by tidal forces. Motivated by the diamond-cell results, he considered the possibility that a thin reaction zone at the core-mantle boundary might offer an explanation for the anomalous nutation component.

He showed that such a reaction layer can easily account for the nutation signal if the layer contains electrically conducting material, as inferred from experiments. The magnetic-field lines emanating from the core would induce small electric currents to flow in the conducting mixture. These small cur-

rents in turn produce their own magnetic fields. The small magnetic fields interact with the main geomagnetic-field lines, much as poles of a magnet can either attract or repel. In essence, the core and mantle behave as two magnets that push against each other. This coupling affects the nutations. The baseline interferometry data are nicely explained if one invokes a heterogeneous reaction zone that contains metal and is a few hundred meters thick.
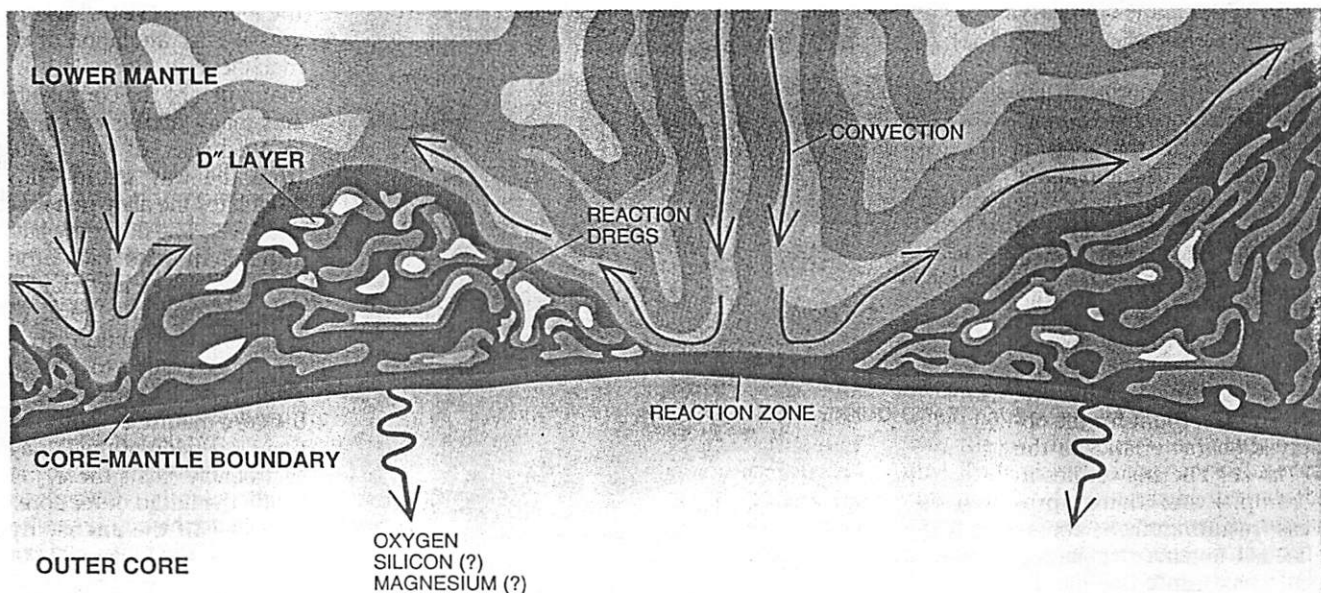
Indeed, our experiments predicted just such a configuration for the reaction zone. The products of the reaction at the bottom of the mantle are expected to consist of a few tens of percent of electrically conducting alloys, such as iron silicide and wüstite. A zone consisting of only 15 to 20 percent alloy would be sufficient to account for the nutations. Thus, our conclusion that the reaction zone would be hundreds of meters thick and would fluctuate in thickness and conductivity along the core-mantle boundary accords well with Buffett's hypothesis.

The second observable surface effect that the core-mantle region influences is the earth's magnetic field. The origin of the main geomagnetic field is well understood, at least in general terms [see "The Evolution of the Earth's Magnetic Field," by Jeremy Bloxham and David Gubbins; SCIENTIFIC AMERICAN, December 1989]. A dynamo effect, rather than conventional magnetism of the iron in the core, pro-

duces the geomagnetic field. (Iron is no longer magnetic at either the pressures or the temperatures existing in the core.) The churning of the liquid-metal outer core essentially acts as an electric current moving through wire. Like the wire, the core then generates a magnetic field around itself.

Convection powers the motion of the molten outer core. The hot liquid from deep inside rises toward the cooler top of the core. The movement transfers heat upward and causes a convective flow. Cooler liquid from near the core-mantle boundary sinks downward and thus also helps to power the convection. Additional sources of convection, such as internal separation of solids and liquid in the outer core, are possible. In this way, the mechanical energy of convection—fluid flow in the outer core—is converted to magnetic energy.

The principles that govern this process are called magnetohydrodynamics—a combination of hydrodynamics, or the physics of fluid flow, and electromagnetism. The mathematical equations behind the process, however, are so complicated that no one has been able to solve them in complete generality. As a result, the solutions obtained are based on physically plausible but greatly simplified assumptions. The solutions obtained from these assumptions do not necessarily explain the small but observable details of the earth's magnetic field, such as the slight ripples in the field intensity. Perhaps the discrepancy results from one of the tra-
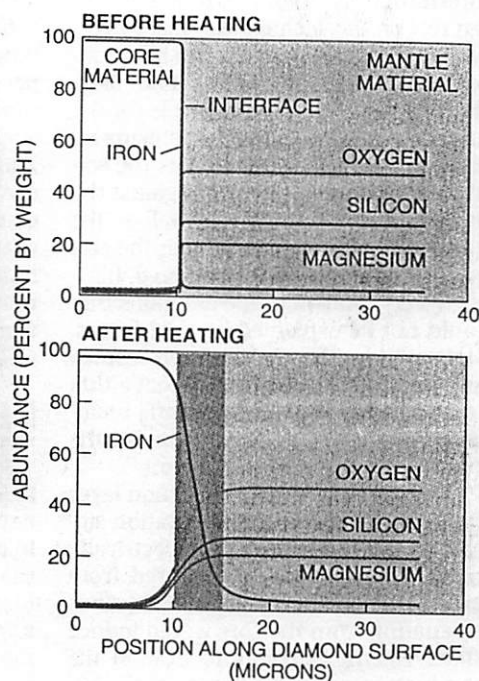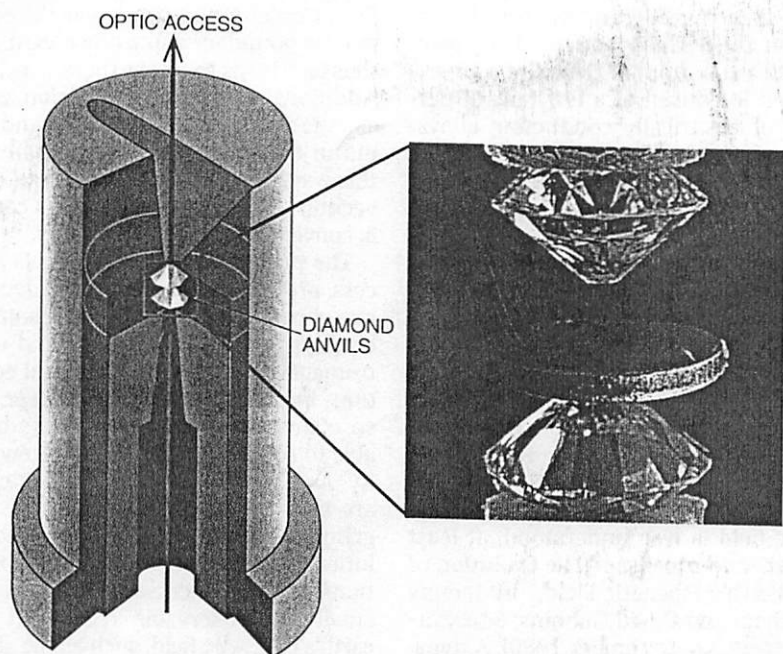

LOWER MANTLE
D" LAYER
CONVECTION
REACTION DREGS
REACTION ZONE
CORE-MANTLE BOUNDARY
OXYGEN
SILICON (?)
MAGNESIUM (?)
OUTER CORE

D" LAYER forms as a result of chemical reactions between the core and mantle. In essence, the mantle rock partly dissolves in the liquid iron of the outer core, producing metal-rich "dregs" that are deposited on the core-mantle boundary. Convection in the mantle tends to disperse the products under downwelling regions and to build up material at upwellings. A thin layer enriched in oxygen and possibly silicon and magnesium may exist on the inner side of the core-mantle interface.

The Diamond-Anvil High-Pressure Cell

This device (*left*) can duplicate the pressures and temperatures of the deep earth. The material to be squeezed and heated is placed in a metal-foil gasket between the tips of two diamond anvils (*photograph*). Turning a thumbscrew (*not shown*) brings the anvils together, compressing the sample. A laser beam can be focused through the diamond to heat the sample. Compositional profiles (*right*) show the abundance of iron, oxygen, silicon and magnesium (elements at the core-mantle boundary) before and after heating. The amounts have been plotted against the element's position on the surface of one of the diamonds, as measured from an edge. After heating, the interface region broadens, spanning between about 10 to 15 microns. The broadening indicates that the elements have reacted. The reaction produces a mixture of metallic alloys (FeSi and FeO) and insulating oxides ($MgSiO_3$ and SiO_2).

OPTIC ACCESS

DIAMOND ANVILS

BEFORE HEATING

CORE MATERIAL · IRON · INTERFACE · MANTLE MATERIAL · OXYGEN · SILICON · MAGNESIUM

AFTER HEATING

IRON · OXYGEN · SILICON · MAGNESIUM

ABUNDANCE (PERCENT BY WEIGHT)

POSITION ALONG DIAMOND SURFACE (MICRONS)

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ditional simplifications used in the calculation: that the metallic core is surrounded by an electrically insulating region, corresponding to the mantle. Geophysicists are now recognizing that the lowermost mantle is not completely insulating but consists of a heterogeneous mixture of metallic alloys and insulating silicates.

Motivated by this information, Friedrich H. Busse of Bayreuth University in Germany recently reexamined the magnetohydrodynamic equations. He discovered an entirely new class of mathematical solutions to the dynamo problem that result directly from the variations in electrical conductivity in the lowermost mantle. The solutions depend on two major factors. One is that the geomagnetic-field lines are essentially "frozen" into the liquid metal of the outer core. So, locked into place, the field lines move only with the convective flow of the liquid outer core. The second factor is that metallic regions embedded within the D″ layer interfere with the horizontal movement of magnetic-field lines emanating from the core. The D″ layer can then deflect or pile together the field lines from the core. Both factors would, according to Busse's calculations, create local magnetic fields at the bottom of the mantle. The fields would explain several complexities of the geomagnetic field, including the observed ripples in field strength.

The electromagnetic characteristics of the core-mantle boundary may also affect the reversals of the earth's magnetic field [see "Ancient Magnetic Reversals: Clues to the Geodynamo," by Kenneth A. Hoffman; SCIENTIFIC AMERICAN, May 1988]. During reversals, which occur every few 100,000 years, the magnetic poles seem to follow a preferred trajectory. Such preference seems especially evident for the most recent reversals in the earth's history. S. Keith Runcorn of Imperial College in London and of the University of Alaska has postulated several mechanisms by which the electrical variations of the D″ layer might influence the path of the magnetic poles.

In a sense, then, the dynamics between the core and mantle extend beyond the earth, stretching well into space via the geomagnetic field. We now recognize the planetary importance of the core-mantle interface, and improved technology is certain to clarify how this remote region shapes the evolution of the earth.

FURTHER READING

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