Interesting Times in Geophysics

by Robert Finn

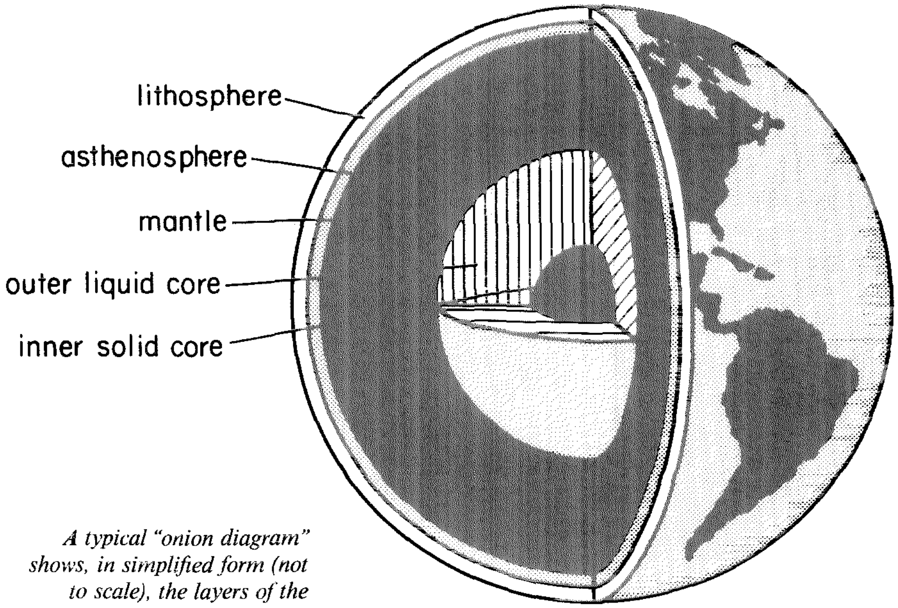
THERE'S AN OLD CHINESE curse that goes, "May you live in interesting times." Someone must have laid this curse on the current generation of Earth scientists. Still reeling from the monumental fight over plate tectonics (the plates won), geophysicists are being confronted by new techniques and new data bearing on the structure of the Earth's deep interior. The varying interpretations of this new data are the subjects of deep disagreements in the geophysical community, and some of the data itself has been called into question. What is certain, though, is that the interior of the Earth is far more complex and heterogeneous than was previously recognized.

If you look at any basic geology text, you'll find an illustration showing the concentric layers of the Earth's interior that makes the Earth look something like an onion with a wedge cut out of it. On top is the *crust*, about 40 kilometers thick under the continents and up to 10 kilometers thick under the oceans. The crust floats on the *lithosphere*, which extends to depths of about 70 kilometers. Under the lithosphere is the partially molten *asthenosphere*, occupying a shell 70 to 250 kilometers in depth. Next comes the solid *mantle*, which contains about 70 percent of the Earth's mass. The mantle is sometimes divided into the upper mantle, a shell about 650 kilometers in depth, and the lower mantle, which extends from 650 kilometers down to 2,900 kilometers. Below the mantle is the molten *outer core*, extending from 2,900 kilometers to 4,980 kilometers. Occupying the very center of the Earth is the solid *inner core*. With a radius of about 1,400 kilometers, it is roughly the same size as the moon.

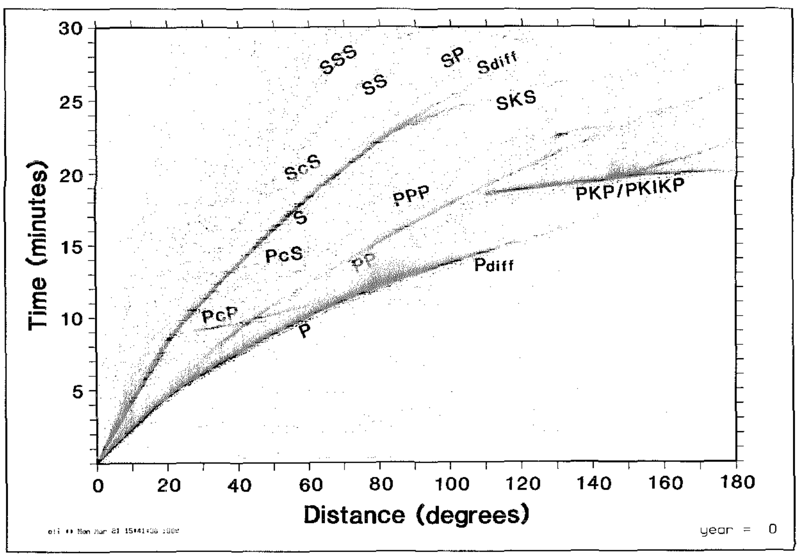
This onion diagram carries with it certain implications that are turning out to be either oversimplifications or simply incorrect. It implies, for example, that the transitions between the layers are both smooth and abrupt and that each layer is internally homogeneous. Geophysicists are now discovering that the transitions between layers are occasionally bumpy, and that within some of the layers there may be a great deal of heterogeneity. "To 99 percent accuracy, the Earth *is* an onion," says Robert Clayton, associate professor of exploration geophysics. "But what's left is a very important 1 percent."

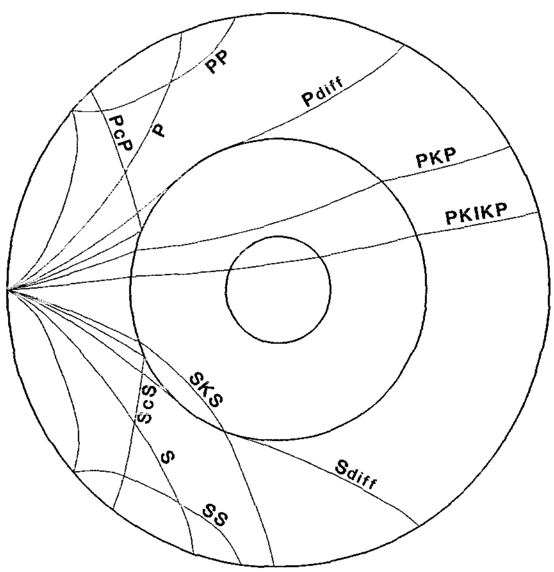
The problem is: How do you get at that important 1 percent? Geophysics is unlike most other scientific disciplines in that its main subject—the interior of the Earth—is almost completely hidden from view. An astronomer can look at distant galaxies through a telescope, a biologist can view cells through a microscope, and a physician can visualize internal body structures with x-rays. But until recently there has been no comparable technique in geophysics.

Surprisingly, it was a medical technique—the CT (computerized tomography) scan—that gave geophysicists the clue they needed to develop a means for imaging the Earth's interior. In the CT scan x-rays crisscrossing through the body are sensed by a circular array of detectors. The information from these detectors is integrated by a computer into a three-dimensional image based on the density of different materials within the body. Clayton, together with several students (John Fawcett, Tom Hearn, Eugene Humphreys, Olafur Gudmundsson, Hua-Wei Zhou, and Huw Davies) realized that a similar technique could be used to image the Earth's interior. X-rays don't penetrate the Earth, but the pressure waves (P waves) and the shear waves (S waves) produced by natural earthquakes do. If the earthquake is



A typical "onion diagram" shows, in simplified form (not to scale), the layers of the Earth's interior.





Earthquakes produce shear (S) and pressure (P) waves that are reflected and refracted by the Earth's internal structures. These diagrams show that S and P waves are received at different times, depending on the distance of the seismographic station from the quake's epicenter and the paths taken by the waves.

large enough—above a magnitude of 4.5 or so on the Richter scale—these waves will be detected at distant seismographic stations after being reflected and refracted by structures deep within the Earth.

Consider, for example, two seismometers in two different locations, each detecting a single earthquake. The quake produces P waves that descend into the mantle and are continually refracted until they return to the surface. The ascending P waves will first reach the closer of the two seismometers, then the more distant one, and the expected travel times can be calculated. Sometimes, though, the P wave will arrive at a seismometer slightly ahead or slightly behind the time predicted by a model that assumes a homogeneous, onion-skin mantle. One way to account for these anomalies is to postulate that the mantle is *not* homogeneous, that there is something somewhere on the P wave's path that speeds it up or slows it down. But with a single earthquake there's no way to tell exactly where along that path this anomaly might be.

Seismic tomographers look at the P waves produced by many thousands of earthquakes, each detected at about 3,000 surface stations. This produces literally millions of data points, each representing the time it takes for a P wave to reach a single seismometer. Since the paths of all these millions of P waves are known, and since they crisscross each other many times, the locations of the travel-time anomalies can be pinpointed.

And seismic tomographers don't restrict themselves to a single type of P wave. They have quite a menagerie of P waves from which to choose, and each of them travels around the Earth's interior in a different way. PcP waves, for example, descend so deeply into the mantle that they bounce against the core-mantle boundary before being refracted to the surface. PKP waves actually penetrate the liquid outer core and are refracted there before re-entering the mantle and finally ascending to the surface. PKIKP waves penetrate the inner as well as the outer core. Each of these waves can be distinguished and each provides different information about the Earth's internal structure.

Another type of tomography—surface-wave tomography—was also developed at Caltech by former postdoc Ichiro Nakanishi; Don L. Anderson, professor of geophysics and director of the Caltech seismological laboratory; and Toshiro Tanimoto, assistant professor of geophysics. These waves, as their name implies, travel over the surface of the Earth, but also penetrate deep into the mantle and can provide useful information on the Earth's interior.

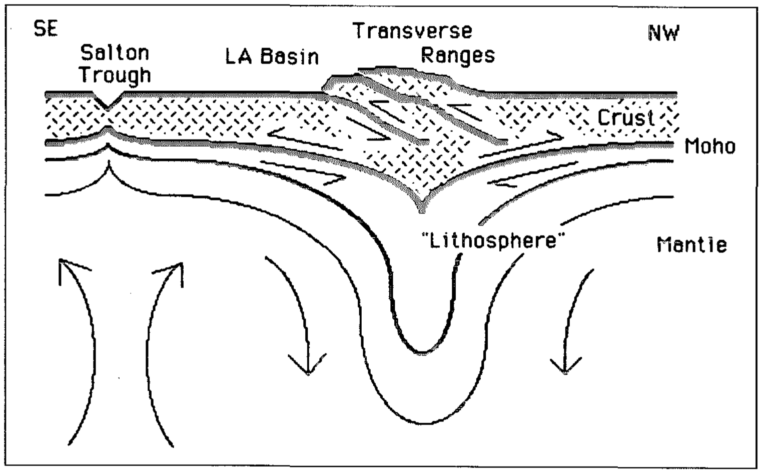
Using arrival-time data from the various types of P waves, geophysicists have built up three-dimensional images of the mantle that map the points where seismic waves travel faster and more slowly than normal. The next question is: Just what is causing these differences in travel time? Usually, the denser the material they pass through, the faster seismic waves travel. (This is also true of sound—a more familiar type of pressure wave. Sound travels faster in water than in air, and faster in steel than in water.) Density differences in the mantle are generally ascribed to temperature differences; seismic waves move faster in cold areas and more slowly in hot areas.

Convection

These temperature differences arise from the mechanisms that have generated heat in the mantle by radioactive decay and have brought heat to the surface from the core throughout the Earth's history. It's extremely important to understand these mechanisms since heat coming to the surface ultimately controls phenomena such as volcanoes, earthquakes, continent formation, mountain building, and the large-scale movement of tectonic plates.

It has long been known that the movement of heat from the interior occurs too rapidly to be accounted for by mere conduction. A far more rapid method of heat transfer—convection—must play an important role. Convection takes place in materials that are sufficiently hotter in one place than in another and have the ability to flow. In such a situation, the heated material expands, becomes less dense, and rises to the top. Once it does so, it cools, increases in density, and falls back to the bottom. We are all familiar with convection in liquids—boiling soup is a well-known convective system. Although it may seem counter-intuitive, convection is also possible in solid materials like the rock of the Earth's mantle. Mantle rock heated at the core expands and rises, albeit very slowly. Cooler rock closer to the surface sinks back down into the deep mantle. Techniques to simulate convective flow in the mantle have been developed by Bradford Hager, associate professor of geophysics, graduate students Scott King and Walter Kiefer, and research fellow Michael Gurnis.

Clayton, Hager, and Humphreys used seismic tomography to reveal a convection cell in the upper mantle directly beneath southern California. The hot, upwelling segment of the convection cell is centered near the Mexican border, and the cold, downwelling segment is located directly beneath the Transverse Ranges—the east-west string of mountains (including the San Gabriels just north of Pasadena) running along both sides of the San Andreas Fault. The seismic velocities in the downwelling are 3 percent faster than its surroundings, which translates to a temperature difference of about 400 degrees. A narrow, cold, slab-like protrusion, this downwelling probably provides the buttressing for the Transverse Ranges. But this is a relatively small convection cell in the upper mantle, a mere eddy of the much larger convection cells circulating throughout the body of the mantle. Some of these larger cells have upwellings at spreading mid-ocean ridges and downwellings at subduction zones. This is how convection controls the movements of large surface plates. On a more global basis, former postdoc Henri-Claude Natof, Nakanishi, and Anderson found giant upwellings in the central Pacific and under northeast Africa—the Afar Triangle region. Tanimoto has now used surface waves to map upwellings in the lower mantle as well.



This idealized cartoon represents a cross section of the crust and upper mantle cut approximately parallel to the San Andreas fault in southern California. Caltech geophysicists have detected a local convection cell with upwellings associated with crustal extension beneath the Salton Trough, and downwellings underneath the Transverse Ranges.

Discontinuities in the Mantle

The nature of large-scale convection within the mantle is still the subject of great debate. At issue is whether the entire mantle is part of one convecting system, or whether there are barriers within the mantle through which no convection can occur. The most important of these possible barriers, called the 650-kilometer discontinuity, was discovered at Caltech in the 1960s, and it forms the dividing line between the upper and the lower mantle.

The exact nature of the 650-kilometer discontinuity is unknown. The most important unanswered question about it is whether the materials above and below it are distinct chemical compositions or whether it represents a single material undergoing a phase transition—to a more densely packed crystalline structure that is caused by increased pressure below the discontinuity.

If the 650-kilometer discontinuity is a chemical barrier, then convection cells originating from lower levels would stop there. Geophysicists argue that if convection penetrates the discontinuity, the upper and lower mantle would eventually mix, obliterating any chemical distinction. Only conduction would operate across the discontinuity, but this conduction could set up a smaller set of convection cells operating exclusively at higher levels and controlled by heat coming out of the lower mantle. A careful study of convection patterns near the discontinuity would settle the question of its nature once and for all—if rising and falling convection currents penetrate the 650-kilometer discontinuity, then it must be a phase transition; if the convection currents are discontinuous at 650 kilometers, then it must be a chemical barrier.

While this seems straightforward enough, there are both technical and theoretical considerations that make settling the nature of the 650-kilometer discontinuity an enormous challenge. Seismic tomography as it is currently practiced gives relatively low-resolution images of the mantle, and it is particularly poor in resolving horizontal features. This means that if data from seismic tomography should reveal a column of rising material that appears to penetrate the 650-kilometer discontinuity, one could not conclude that a convection cell is indeed penetrating it. An alternative explanation would be that the convection cell stopped at the discontinuity, that heat conduction set up a separate convection cell above the discontinuity, and that the resolution of the seismic tomography data was too poor to reveal either the horizontal components of the convection cells or the break between the convection cells above and below the discontinuity.

But even if the resolving power of seismic tomography could be greatly improved, the issue would not necessarily be settled. According to Hager, the 650-kilometer discontinuity could be a simple phase transition and still seem to have separate convection regimes above and below. And according to Don Anderson, not only is it possible for convection cells to penetrate a chemical discontinuity without homogenizing everything, but there is evidence that such a mechanism actually operates in the mantle.

Hager has run computer simulations of the convective movements in the mantle to find out what would happen if there were no chemical barrier—just a phase transition at 650 kilometers that results in material 100 times more viscous below the discontinuity than above it. In such a situation, which Hager refers to as "mechanical stratification," convection above the 650-kilometer discontinuity is faster and far more vigorous than below, and the transition between the layers remains very sharp. Yet material from below does penetrate the barrier, although very slowly. What this means is that material in the upper mantle would be very well mixed, while material in the lower mantle would not be as well mixed. Speaking about the controversy between geophysicists who believe in a chemical barrier at 650 kilometers and those who believe in a phase transition, Hager says, with tongue in cheek, "This is almost a religious issue, but I'm no longer religiously involved because I have seen the truth."

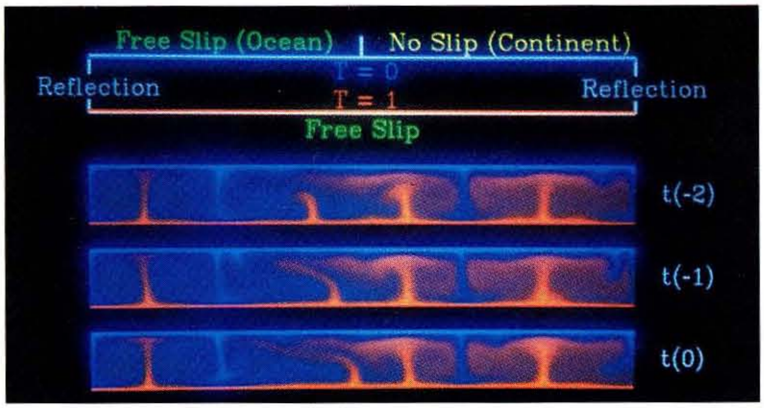
Anderson, on the other hand, believes that in the argument between those who believe that the mantle is homogeneous and those who believe that it is stratified *both* sides are wrong. In Anderson's view, the mantle is neither homogeneous nor is it stratified. He believes that convection can be penetrative without being homogenizing. In fact, says Anderson, convection can actually dehomogenize things. Convection can transport light material from the depths to the surface, and it can transport dense material from the surface to the depths. These materials can then drop out of circulation and accumulate—light materials on the surface and dense materials as far down as the core-mantle boundary.

Split-pea soup is a good example of this effect of convection. If you let a pot of split-pea soup boil for a little too long, a frothy scum of low-density material will form on the top. Likewise, the heavier solids will accumulate at the bottom of the pot. In fact, it's well accepted that convection did just this during the formation of the Earth. The lighter materials that formed the crust ended up as a thin scum on top and the heavier materials, most notably the largest proportion of the Earth's iron, sank to the core. Anderson claims that this kind of dehomogenization, occurring during accretion is, by and large, irreversible, and it also made the lower mantle different from the upper mantle.

Concentrating on another discontinuity—this one at 400 kilometers—Anderson's studies have convinced him that material from the middle mantle (400 to 650 kilometers) has penetrated the upper mantle without any substantial mixing. Evidence for this comes from the isotopic composition of ocean-island basalts. These basalts have a different isotopic composition than does regular ocean crust, and Anderson interprets this in the following way: When a convection cell originating in the middle mantle (or below) first penetrates the upper mantle and comes to the surface, it is contaminated with upper-mantle material and it forms ocean-island basalts. Later, the convective upwellings punching through the upper mantle become broader and less contaminated, forming regular ocean crust. Likewise, the downwelling parts of the convective cells can penetrate through the upper mantle, contaminating it with sediments, and taking the bulk of the oceanic lithosphere down to the middle mantle. Anderson is tantalized by evidence that indicates that a layer called D″ (pronounced "dee double-prime") at the core-mantle boundary may have formed from material that was once on the surface of the Earth. The material in the middle mantle (400 to 650 kilometers) appears to recycle between the surface and the middle mantle.

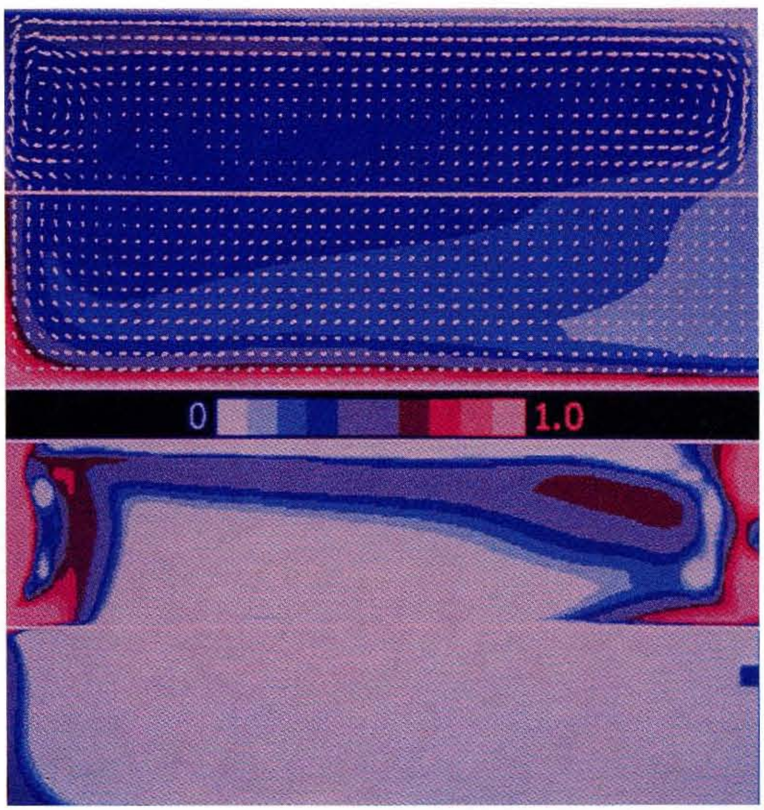
Leon Silver, the W.M. Keck Foundation Professor for Resource Geology, thinks things are far more complex than that. A pioneer in geochronology, Silver has been able to determine the dates of formation of continental rocks with exquisite precision—better than two parts in a thousand even for rocks that are more than a billion years old. Using this geochronological data, Silver has built up a detailed history of the formation of the North American continent. He finds that even within granites that formed in a single geological generation there are a number of different isotopic signatures. This must mean that there are a number of isotopically distinct reservoirs in the upper mantle.

"The problem with geophysical observations is that they lack historical perspective," says Silver. "Geophysicists only look at a slice of geological time. For a historical perspective you've got to look to geology and geochemistry. Continents are ultimately extracted from the upper mantle, so they are the principal recorders of the evolution of the Earth's upper mantle reservoirs. If continents have a complex history—and my studies show that they do—then the mantle must have a complex history."



Above: Simulations of convection within the mantle reveal differences between areas lying beneath continental and oceanic crust.

Below: Hager has run computer simulations of convective movements in the mantle that assume no chemical barrier—just a phase transition at 650 kilometers (at the panel center) that results in a hundredfold increase in viscosity. The simulations reveal that convection above the discontinuity is faster and far more vigorous than below, and that the transition between the layers remains very sharp. Yet material from below does penetrate the barrier, although very slowly.



Descending Slabs

Not only is the formation of continental crust complex, but its destruction is complex as well. Continental crust is destroyed at subduction zones—areas in which huge crustal slabs dive into the mantle. These areas are thought to correspond to the downwelling arms of convection cells, and at issue is whether the slabs descend all the way to the core-mantle boundary or whether they stop at the 650-kilometer discontinuity.

Using seismic tomography, Clayton and graduate student Hua-Wei Zhou have recently seen cold, slab-like features at a depth of 650 kilometers in the upper mantle under Asia. These appear to be remnants of the Pacific plate that have slipped under the Asian continent. According to Clayton and Zhou, instead of diving into the lower mantle, the slabs appear to sink initially, then they move horizontally after reaching the bottom of the upper mantle.

These findings would seem to support the chemical barrier hypothesis, but the nature of the 650-kilometer discontinuity is still open. The deep slabs broaden as they descend and this may mean that they're being deformed as they push against a barrier. But the barrier doesn't have to be a chemical one; if Hager is correct and the phase transition results in a hundredfold increase in viscosity, you would expect such broadening. In fact, research fellow Michael Gurnis, working with Hager, has done computer simulations that show that when slabs hit this type of mechanical barrier they will first broaden and then break through. This will also happen at a chemical barrier.

Hiroo Kanamori, professor of geophysics, thinks it's significant that earthquakes are never seen at depths below 650 kilometers. "If plates just become mixed with the upper mantle, you'd see earthquakes gradually decreasing with depth," says Kanamori. "In fact, you see increasing activity near 650 kilometers, indicating that something may be hitting against something else. Another possibility is that the slab is going through a phase transition and, as it does so, it weakens, causing earthquakes."

The Core-Mantle Boundary

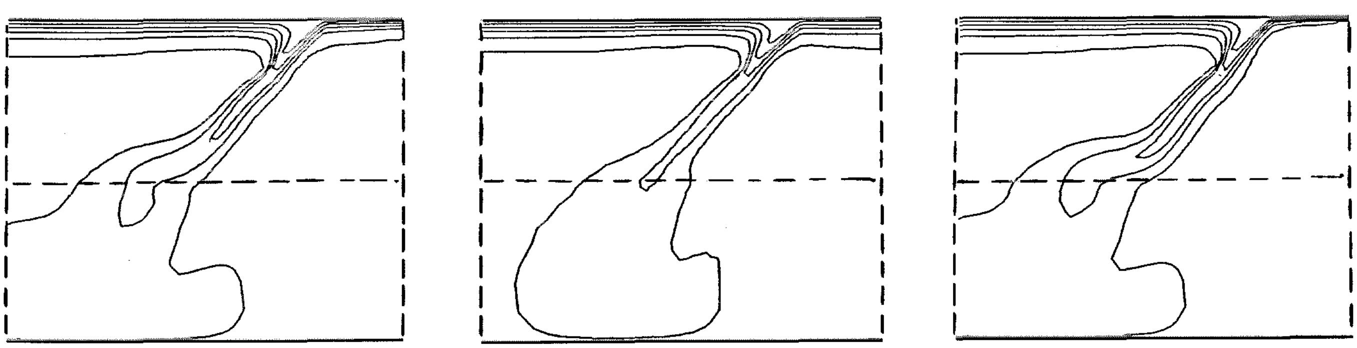
If slabs do descend past 650 kilometers, they probably go all the way down to the core-mantle boundary. This is a region that is turning out to be extremely interesting in its own right. Last year Clayton, Anderson, and graduate student Olafur Gudmundsson announced that studies of three types of pressure waves—PcP (reflected by the boundary), PKP (refracted by the outer core), and PKIKP (refracted by both inner and outer cores)—revealed the presence of high "mountains" and deep "valleys" at the core-mantle boundary. There are mountains (upward-going deflections) as much as five kilometers high under Australia, the Labrador Sea, and off the Pacific coast of South America. Valleys (downward-going deflections) of similar depth were found under the southwest Pacific, the East Indies, and southern Europe.

These contour images of the core-mantle boundary are still of comparatively low resolution, but they may have a great deal to say about convection patterns in the mantle. Most geophysicists believe that the mountains are the starting points of upwelling convection currents and that the valleys are the end points of downwelling currents.

The mountains and valleys reside within the D″ layer at the core-mantle boundary. This layer is turning out to be extremely heterogeneous and may, in fact, be composed of different materials than the rest of the mantle. Recent studies of the melting point of iron at the intense pressures—over 3.5 million atmospheres—in the core suggest that the core's temperature may be thousands of degrees higher than was previously believed. These studies, conducted by Thomas Ahrens, professor of geophysics, and Raymond Jeanloz of the University of California, Berkeley, who's now a Sherman Fairchild Distinguished Scholar at Caltech, revealed that the temperature of the solid inner core is about 6,900 K, and the temperature at the core-mantle boundary is about 4,800 K.

"D″ must be a chemically distinct layer," maintains Hager. "The temperatures in the

These simulations by Michael Gurnis show that when crustal slabs descending from an oceanic trench hit a mechanical barrier—in this case a thirtyfold increase in viscosity—they will first broaden and then break through. The contours represent "isotherms"—lines of equal temperature. The first panel simulates a time 50 million years after the start of the descent, the middle panel is 8 million years later, and the last panel is 7 million years after that.



core are much higher than at the base of the mantle. The only way to have such a mismatch would be to have an insulating layer of chemically distinct material. D″ may be old oceanic crust that has sunk to the core-mantle boundary. Or it may be a mixture of stony mantle material and metallic material from the core that makes D″ too dense to participate in convection." Another possibility, proposed some years ago by Anderson and graduate student Larry Ruff, is that D″ is the high melting-point residue of the mantle and core that formed during the Earth's accretion.

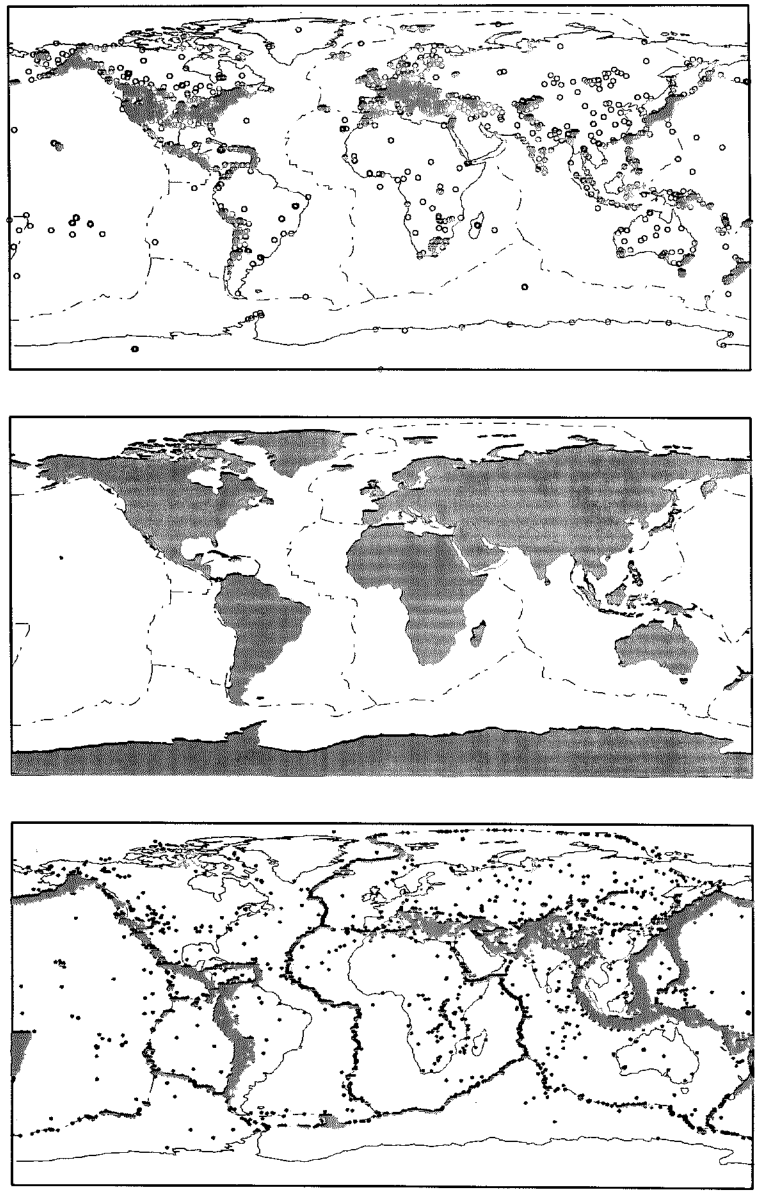
Toshiro Tanimoto has mapped D″ and has concluded that it is a highly irregular structure—as much as 300 kilometers thick in some places and as little as 100 kilometers thick, or possibly even absent, in others. These variations make D″ seem similar to the crust, and like the crust it may be forming, reforming, and shifting. In fact, some geophysicists refer to "anti-oceans" and "anti-continents" existing there.

In the course of the Earth's rotation there must be some torque produced at the core-mantle boundary as the molten core sloshes against the mountains and valleys. Last year Clayton, Hager, Mary Ann Spieth of JPL, and others announced the results of calculations indicating that this torque may account for a long-known jerkiness in the Earth's rotation that causes the length of the day to vary by about five milliseconds over a decade. More recent calculations, however, reveal that five-kilometer depressions would cause more jerkiness than is actually observed. Some seismologists now believe that upward-going dimples in the core-mantle boundary may be filled with huge inverted lakes. These lakes would be made up of a lower density layer of molten silicates, floating on top of the rest of the molten core. Such lakes would shield the mantle from motion in the core just as the oceans shield the sea floor from the effects of winds. This hypothetical new layer, called E′, will be hard to visualize by direct seismic methods, but its presence may be needed to reconcile various types of geophysical data.

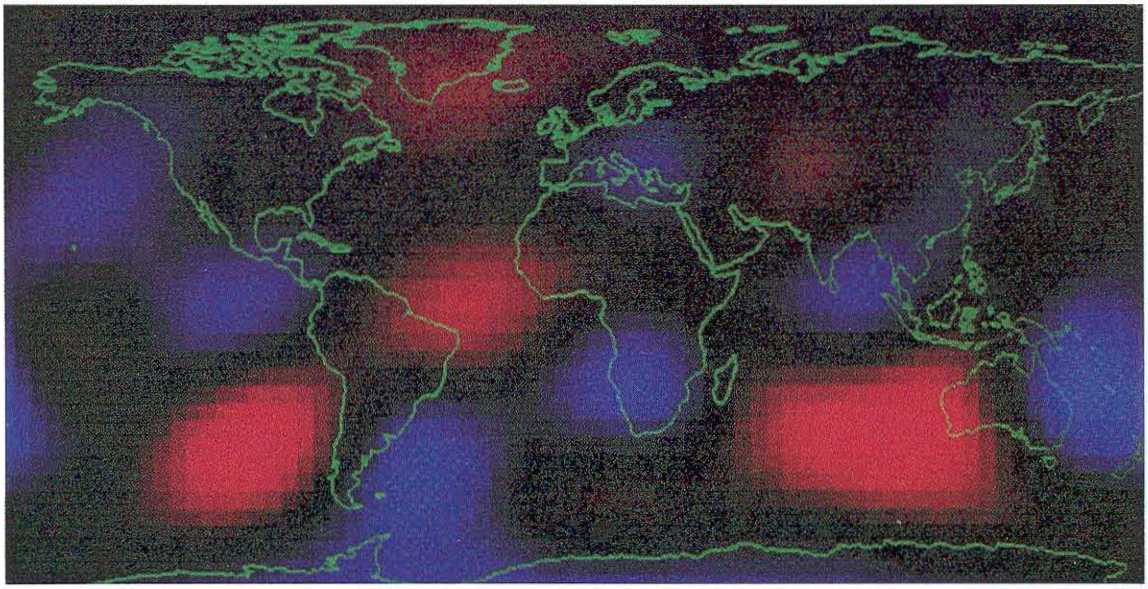
Anisotropy in the Outer Core

And it's turning out that the outer core may itself be more than just a uniform liquid. Gudmundsson, Clayton, and Anderson have found that waves traveling near the center of the Earth traveled faster if they paralleled the Earth's axis (that is, moved north and south) than if they traveled across the equatorial plane. Scientists from Harvard University showed last year that waves traveling through the solid inner core showed this "anisotropic" behavior, but the Caltech group has now shown that this behavior extends unexpectedly into the molten outer core and possibly into the base of the mantle.

There are at least four possible explanations for this anisotropy. According to Anderson, the most likely explanation is that part of the liquid core is actually solid, like a slurry. In physical terms, this means that the molten iron alloy of the outer core may be the site of "rainstorms" in which the "raindrops" are iron filings. Part of the molten core does not behave entirely as a liquid, but has some crystal-like properties. The iron particles are freezing out in the colder



The top panel shows the worldwide distribution of seismic stations, and the bottom panel shows the worldwide distribution of earthquakes. Locations of continents and plate boundaries (dashed lines) appear in the center panel.



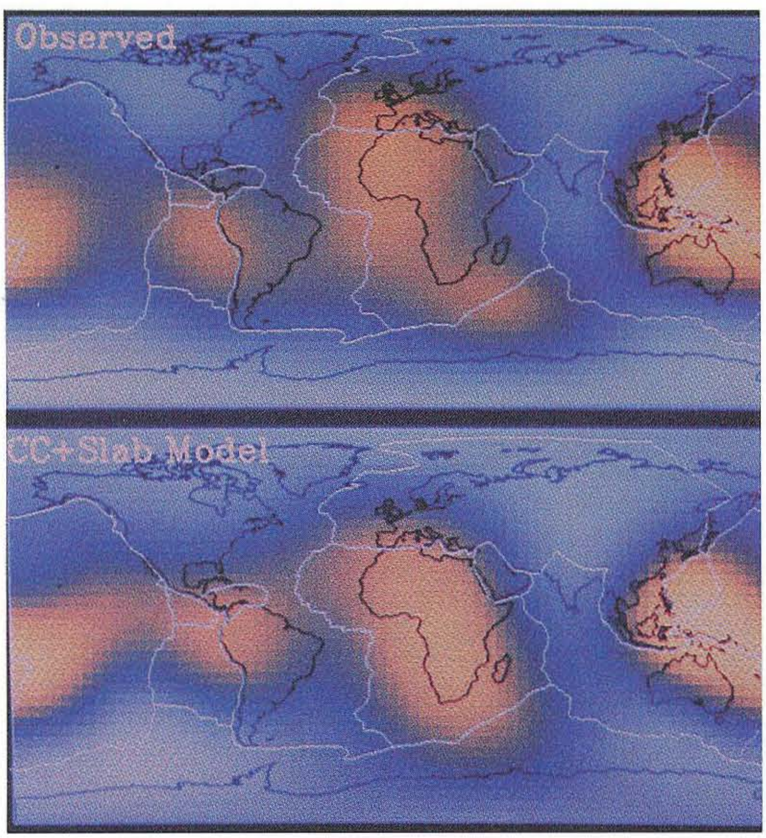
The red blobs on this map represent upward-going deflections ("mountains") on the outer core, and the blue blobs represent downward-going deflections ("valleys").

downwelling parts of the core and are remelting in the warmer upwellings. Some of the solid iron plates out on the inner core, causing it to grow with time.

A second possible explanation of the anisotropy could be the existence of a previously unknown supermagnetic field in the core, which could slow down seismic waves moving parallel to the equator. No evidence of such a magnetic field has ever been found, however. Extremely fast fluid motions within the core form the third possible explanation. If the motions were in just the right direction and at just the right velocity, they would cause seismic waves to speed up parallel to the axis, just as the wind sometimes carries sounds. Anderson regards this explanation as highly improbable.

Hager favors a fourth explanation—that the core is about one kilometer more ellipsoidal than the generally accepted standard value. "I think it's unlikely that showers of crystals are continually being produced in the outer core," says Hager. "For this to happen you'd need a constant flux of heat from the core to cool it down." But Anderson believes that iron is constantly freezing and melting in the core, depending on location. The net freezing rate, which can be calculated from the size of the solid inner core, is just about what is expected from heat flow from the core. Anderson points out that the inner core is solid, and therefore the bottom part of the outer core must be near the melting point.

Hager used P-wave data to calculate regional variations in the density of the Earth. From these he modeled the Earth's geoid (the hypothetical shape of a rotating, fluid-covered Earth) and calculated regional variations in the gravitational field. The calculated gravitational field showed more than 90 percent agreement with the measured gravitational field.



The Quality of the Data

Interpretations of seismic tomography data are not the only things geophysicists argue over. The quality of the actual data has frequently been called into question. One problem is that earthquakes and seismographic stations are not distributed uniformly around the globe. Relatively high resolution can be obtained only from areas where there are many earthquakes and many seismometers. Unfortunately, some of the most interesting regions in the world—notably the mid-Pacific—are subject to the lowest resolution.

In addition, body-wave seismic tomographers do not get to use raw data from the thousands of earthquakes that are detected at the thousands of seismographic stations around the world. (Surface-wave tomographers do use raw waveforms.) Body-wave tomographers get a single figure—the arrival time of the P wave—that a local observer has determined from measurements of an analog seismograph recording. These data can be compromised in several ways.

First of all, seismograph quality varies enormously. Some seismometers, for example, are in locations that are subject to a great deal of background activity, and this makes determining exact travel times difficult. Secondly, the local observers themselves certainly vary in their skill at seismograph-reading. Since there are millions of individual data points, random errors in the data will tend to cancel themselves out. But systematic errors are a much greater problem, since they are a problem of unknown magnitude.

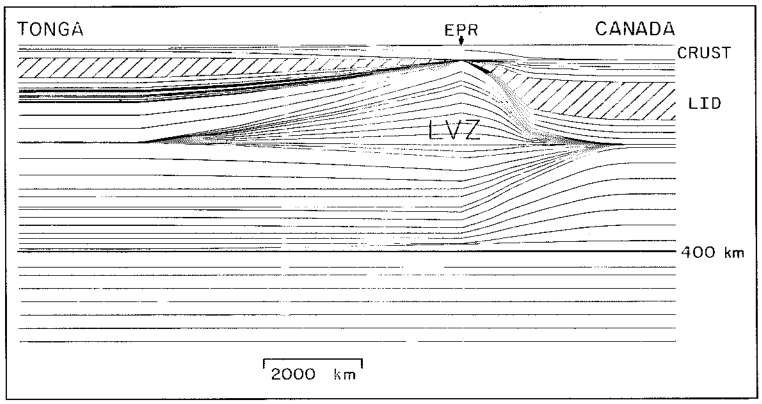
For this reason, Hiroo Kanamori is skeptical about all results that are based on P-wave arrival times. And in his view, the results become less believable the farther down one goes. "We have a reasonably good picture of the crust," he notes. "In the past decade we've gathered a lot of good data, and our computer power has increased. Our knowledge is obviously still too sparse, but at least the data quality is good. Our picture of the upper mantle is OK—large, long wavelength features are known. Qualitatively, this is not very different from 20 years ago, though our knowledge is more objective now. But it's far more difficult to understand the structure in the lower mantle, because in order to do so we must first understand the structure of the upper mantle very well. We have a great deal of P-wave data, but in my opinion the quality is very poor."

But Hager defends the quality of the data used by seismic tomographers. He points to a study in which he used the P-wave data to calculate regional variations in the density of the Earth. From these he modeled the Earth's geoid (the hypothetical shape of a rotating, fluid-covered Earth) and calculated regional variations in the gravitational field. The calculated gravitational field showed more than 90 percent agreement with the measured gravitational field and this, says Hager, tends to validate the P-wave data, at least for long-wavelength features.

New Methods for the Future

"In order to resolve all these conflicting interpretations we need finer detail," says Kanamori. "For example, how thick is the 650-kilometer discontinuity? Is its depth the same from place to place? We need more data from broad-band digital seismometers, where operator error is much less of a factor. But there are fewer than 50 digital seismograph stations worldwide." This situation may soon improve, however. The Caltech Seismological Laboratory is trying to raise $4.2 million to add 10 broad-band digital seismometers to the 300 analog instruments in the Southern California Seismic Array.

In addition, Kanamori believes that one can gather higher-quality results by looking at S waves, as do Tanimoto and Donald Helmberger, professor of geophysics. Aside from looking at a different type of wave, both researchers differ from those who study P waves in that they examine the entire waveform, not just its arrival time.



By studying interference patterns in S waves that take different pathways from source to seismometer, Helmberger is able to build up far more detailed images of the Earth's internal structure than is possible using P-wave arrival-time data. This diagram shows the results of his approach—a relatively detailed picture of a slice of the Earth running from Tonga in the South Pacific to northeastern North America. (EPR is the East Pacific Rise in the Gulf of California, LID is the lithosphere, and LVZ is the low-velocity zone in the mantle.)

Helmberger, for example, is actually able to detect interference patterns in S waves that take different pathways from source to seismometer. In this way he builds up far more detailed images of the Earth's internal structure than is possible using P-wave arrival data.

"My belief is that geophysics is at a turning point," says Kanamori. "We have really powerful computers and we have good techniques. But the quality of the data is simply falling behind. The reason there are so many different views about the Earth's internal structure is that it's hard to interpret low-quality data. With a new generation of higher quality data we may be able to resolve these issues. It may be an exciting time to be a geophysicist, but the real excitement will come when we can make definitive statements based on high-quality data." □