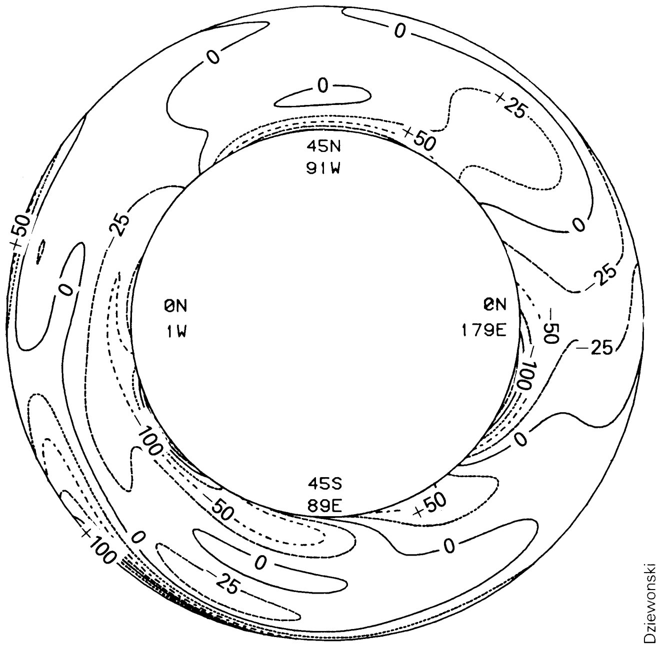
# Inner Geography

By tracking speeds of earthquake waves, scientists are mapping the structure of the earth's interior. Their results may help solve some of the toughest problems in earth science.

*"But you perceive, my boy, that it is not so, and that facts, as usual, are very stubborn things, overruling all theories."*
Professor Von Hardwigg
*A Journey to the Center of the Earth*




Adam Dziewonski

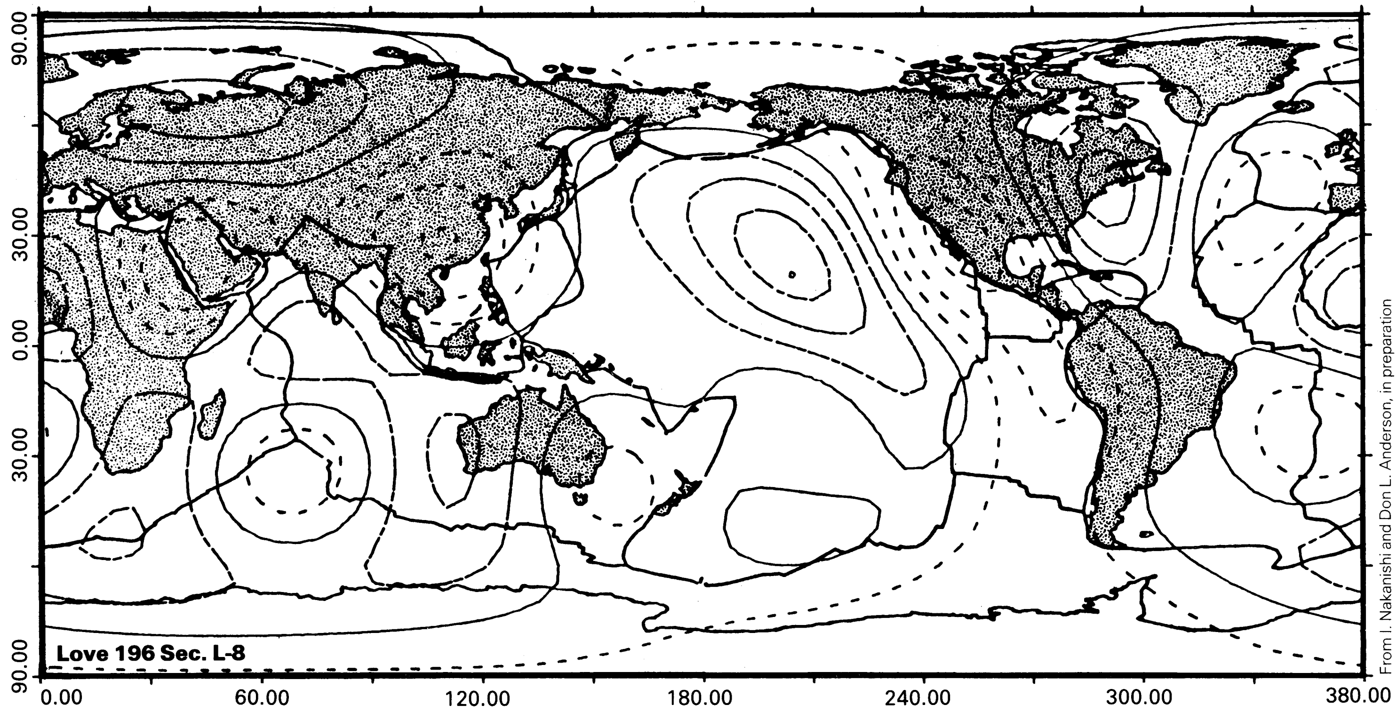
*Until recently maps of the earth's interior were simple diagrams in which concentric circles from the core outward showed general boundaries between major features, such as the crust-mantle boundary. Using information recorded by digital seismometers, scientists now are drawing more detailed maps, like this cross-section of the lower mantle. Wavy lines delineate areas where seismic waves speed up or slow down as they make their way through the earth.*

By CHERYL SIMON

Professor Hardwigg and his reluctant companion Harry embarked on their journey into the earth's recesses armed simply with food, tools, weapons and some basic theories about the earth's interior. Some facts about the earth, such as that at relatively shallow depths temperatures would have been sufficiently high to cook the heroes, were waived in the just cause of good storytelling by the tale's creator, Jules Verne. The professor's modern counterparts — geophysicists and seismologists—know that a true excursion to the earth's center is impossible. Even the deepest holes drilled into the earth extend through only one-tenth of the topmost portion, the crust. But still the scientists want a map.

Though an eyewitness account of features of the earth's structure is out of the question, for the first time a detailed map is within reach. For more than a decade a network of seismometers scattered around the world has been producing a continuous record of digital data of the earthquakes that frequently shudder through the planet. When a quake happens, it disturbs the earth and spreads seismic waves through the planet in all directions from the center, or focus, of the rupture. Now scientists are compiling and interpreting the seismic data in the first concerted efforts to produce a three-dimensional map of the earth's interior.

Granted, a few gross features are already known. Studies of the mantle, the vast portion of the earth that lies between the core and the thin coating of crust, show several points where travel times of seismic waves change dramatically. These zones, called discontinuities, occur at the




*Contour map shows changes in speeds of Love waves traveling over the earth's surface. (A Love wave moves horizontally and its speed depends on the density and rigidity of the material through which it passes.) Short dashes represent slow areas; long dashes indicate fast areas. Western North America, the eastern Pacific, Southeast Asia and the Red Sea area are the slowest regions, indicating hot upper mantle. Eastern North America, northern Europe and the central Pacific are the fastest areas.*

crust-mantle boundary or "Moho," and at depths of 400 kilometers and at 670 km, the dividing line between the upper and lower mantle.

In the present studies it is the mantle that commands most attention. With the general acceptance in the 1960s of plate tectonics—the idea that the earth's crust is made up of moving plates and that new seafloor is created continually at spreading centers where molten rock wells up from the mantle—another view was accepted as well. This view says that the molten material must circulate, moving slowly as the earth attempts to rid itself of the tremendous heat contained in its radioactive core. This motion is known as convection.

A simple analogy of mantle convection is the movement of water boiling in a pot. The hottest water, near the flame, rises to the surface. There it cools and sinks back to the bottom only to be reheated and again sent upward. Material in the mantle must move in the same way, scientists reason, with hot material rising at spreading centers on the ocean floor. Over thousands of years the melted rock hardens into ocean crust. As it does so it is carried away from the spreading center as new seafloor is created. Eventually, cold and dense, the oceanic lithosphere—the crust and the topmost part of the mantle—is dragged back into the earth along subduction zones.

Much of the excitement over the mapping project is related to the issue of convection. While it is known that the plates move, along with their passengers the continents, it is not known what mechanism drives them. A picture of the scale and location of convection will add needed facts and fuel to a long-standing argument among earth scientists, and may even solve it. What is the nature of this convection? Is it confined, as some scientists believe, to the upper mantle? Or does the whole mantle circulate in huge cells that extend all the way to the core? Does the lower mantle convect separately from the upper mantle, or is there some mixing between the two regions? Opinions on each likelihood abound.

Perhaps, as Professor Hardwigg surmised, the facts will overrule the theories.

The three groups of researchers tackling the problem are using similar approaches but they differ in application. Adam M. Dziewonski and John H. Woodhouse of Harvard University are studying both the upper and lower parts of the mantle. For the lower mantle they take hundreds of thousands of measurements compiled by the International Seismological Center in Reading, England, and feed them into a computer. Because seismic waves for each earthquake travel all around the world, their paths reveal some information about the average structure of the earth.

The Harvard scientists begin with a blank image of the earth, a model in which the speed of each wave is equal. They then proceed to chart the paths of hundreds of thousands of seismic waves. Because the waves move through hotter material more slowly than through cooler material, when real information about a seismic wave is charted, it shows how much the wave's velocity deviates from the predicted average speed.

The path of a single seismic wave reveals very little, but when many waves are charted, a picture begins to emerge. A diagram of a cross-section of the earth shows irregularly shaped structures within the lower mantle. The shapes and sizes of the features are defined by the changing speeds of the seismic waves. These features may be convection cells in the lower mantle, Dziewonski says, or they may represent zones where the chemistry of the mantle changes, altering the behavior of the seismic waves. For example, waves would pass more slowly through iron-rich material.

Their study of the upper mantle uses recordings of surface waves—the shapes the seismic waves take, and the ways the ground is displaced over time when an earthquake occurs. Since 1981 the researchers have used the data to define the sources of selected earthquakes. Now they are adjusting their model to study the earth's interior in three dimensions. "In order to obtain better agreement between the observations and the data, we have to revise our notions and make small revisions in the structure of the earth," Woodhouse says. Presumably, the surface features are a product of processes deep in the earth. In a switch from traditional approaches to seismology, the researchers are not measuring directly the properties of waves. Instead, they are trying to change the model of the earth to match the seismograms, or records of the earth's vibrations.

The researchers believe their early results argue strongly for separate convection in the two mantle layers. "We don't see anything in the lower mantle that would in any way remind us of things that are going on at the surface," such as plate motions, Dziewonski says. "There is a hedge in that: The convection pattern may be very complicated." Nonetheless, he says, the results seem to preclude the entire class of models that depict whole-mantle convection.

At Scripps Institution of Oceanography in La Jolla, Calif., other researchers are using much the same information but in applying it differently, are coming up with quite different results. They are looking at the structure of the earth in areas where earthquakes occur deep in the mantle. The deep focus quakes, which happen where cool slabs of oceanic lithosphere descend into the mantle, occur no deeper than 670 km. At this point too, the seismic waves pick up speed as the mantle's mineral structure and possibly chemical composition changes. "People who believe in upper mantle convection believe this discontinuity is a chemical transition," says Thomas H. Jordan of Scripps. In this view, he says, the upper mantle has one composition, the lower mantle another, and the differences keep convection in the two layers separate.

But Jordan sees difficulties for the model that separates convection. His studies of speeds of seismic waves show that below the zone of deep focus quakes there is a region where the "seismic wave velocities look just like a continuation of the slabs." This may be evidence, he says, that the slabs do not stop at depths of 670 km to 700 km. Instead they drive on into the lower mantle.

If the preliminary results of the two groups seem contradictory, none of the researchers seems much concerned. While they hope for early success, the scientists are rubbing their hands in anticipation of a good-natured but spirited debate. "One of the exciting aspects of science is when there are two different schools of thought that come up with different conclusions. You can be assured that something is about to happen that will be a watershed—a result that will reset everybody's thinking," Jordan says.

A research team at the California Institute of Technology in Pasadena is taking yet another approach to the problem. Scientists there are refining a computer program that will allow them to attempt to chart the earth's features using a technique similar to the tomographic methods used in medicine. Caltech's Robert W. Clayton explains that in medicine, an X-ray is fired through a particular part of the body. As the ray moves it loses intensity, or attenuates, as it travels through material of different densities. The anomaly is measured, and technicians project the path of the ray back in the direction from which it came. The patient or the X-ray machine is rotated and the procedure is repeated. Finally, the X-ray paths show an image: a tumor in three dimensions.

In their approach to the mapping problem, the Caltech researchers use records of millions of seismic waves moving through the earth at different angles. As a wave moves from the source of an earthquake to a receiver on the surface, its travel time may be different from that predicted. To learn where the seismic wave slowed down or speeded up, the scientists trace it back along its path.

"If you had just one ray, the picture would be blank with just one line coming through it," Clayton says. "By putting many lines through you begin to form an image of where the anomaly zones are."

This method is called body wave tomography. It focuses on specific areas of the mantle. While the global approach used by Dziewonski and Woodhouse predicts the movement of the seismic waves through the entire earth, the tomographic method is local. "We alter the model," Clayton says, "but we never stray very far from where the actual ray was. If there are zones in the earth where there are no rays at all, it would come up with absolutely zero for us."

In another segment of the project, Don L. Anderson and Ichiro Nakanishi, also of Caltech, are tracking surface waves, which zip along the earth's surface in much the way that satellites orbit the planet. This technique, called surface wave tomography, will enable the scientists to compile a global map of surface waves based on their various speeds. The map will be useful because the velocity of each wave depends on qualities, such as temperature and density, of features inside the earth. This is the only approach being taken that will yield information about the directions in which crystals in mantle material are oriented. Those findings in turn may reveal how fast, how deep, and in which directions convection currents flow. Convection probably occurs at roughly the speed that plates spread apart — a few centimeters per year.

The digital data will determine how thorough any map of the earth's interior can be. Limits are imposed by areas where there are few or no earthquakes and by the locations of recording stations, most of which are in the United States, Western Europe and Japan. Relatively little is known about earthquakes focused in areas such as polar regions and ocean floors. Nonetheless, as Anderson says, "The mapping endeavor is moving along remarkably fast." A three-dimensional model including gross details of the earth's structure could be complete in three or four years. Then, researchers will begin to refine the model and to chart smaller features now hidden in the earth.

Explorers of the mantle's structure hope that their efforts, and related honing of techniques and instruments, will illuminate some other murky problems in earth science. For instance, results could help resolve a heated controversy about whether the roots of continents are shallower than the plates or deeper, extending as far as 200 km into the mantle (the plates themselves are thought to be about 100 km thick). If the roots are deep, Jordan says, they certainly affect convection, and the model of convection must be modified to allow for their existence. Proof of deep roots also would require some scientists to revise a long-standing view of the continents as tectonic pawns — splendid structures that move with the plates but have little effect on fundamental earth processes. "This is very controversial," Jordan says. "A whole group of geophysicists thinks it's absolutely wrong" that these roots can exist. "But from my point of view, the seismic evidence is very strong."

The three-dimensional structure also may help explain the relationship between interior processes and the earth's gravity field. Variations in gravity probably are related to the earth's dynamic processes. For instance, if convection is occurring, cold, dense material sinks and hot material rises, each perturbing the gravity field. But gravity signals, such as those recorded by the oceanographic satellite SEASAT in 1978 (SN: 12/4/82, p. 364; 4/2/83, p. 223), do not indicate whether they originate deep in the earth or closer to the surface.

The same question surrounds a worldwide pattern of asymmetry that was detected by Jordan, Freeman Gilbert and Guy Masters, also of Scripps. They reported last year that when they studied seismic waves with very low frequencies, they saw an unmistakable pattern that they believe proves that the earth is not a perfect sphere. While it is known that the earth bulges slightly as it rotates, they say it is less round than can be explained by rotational forces alone.

"We know the geographical shape of the pattern but we can't prove exactly where it is," Gilbert says. "It's shallower than 700 km and deeper than 100 km." The researchers say that the pattern bears an uncanny resemblance to the size and shape of a massive signal seen in the earth's gravity field. Gilbert suspects that the explanation of the asymmetry will be found at about 670 km. Perhaps a three-dimensional map of the earth's structure will tell.

Dziewonski is fond of describing the digital networks as a "seismologist's nightmare." He imagines a seismologist who wakes in the dead of night, his psyche racked with waves of apprehension. There's nothing left for him to do: the advent of digital seismometers has made it possible to "throw a thousand or so traces into a computer and get back the structure of the earth."

On the one hand, Dziewonski says the nightmare is a "joke." On the other, he says that the network of digital seismometers is such a powerful tool that it could reveal everything a seismologist would want to know.

Clayton takes a more sanguine view. "It's going to go around a few times with different techniques before people believe the results. Even if someone were to come up with a very detailed model very soon, we'd still argue about it for a while." □