Developing a Big Picture of Earth's Mantle

The sounds of distant earthquakes, specially combined by large computers, are producing the first global, three-dimensional maps of the mantle

The earth is mostly mantle, from just beneath the few tens of kilometers of familiar crustal rock at the surface down 2900 kilometers to the molten iron core. All of the hubbub at the surface—drifting and colliding continents, volcanic eruptions, earthquakes, and mountain building—is merely a superficial expression of the operation of a great heat engine in which the solid rock of the mantle churns about ever so slowly, carrying the fiery inner heat of the earth toward the surface.

Exactly how mantle convection accomplishes this central geological task has remained a mystery hidden beneath the obscuring veneer of tectonic plates. But the accumulating record of earthquake seismic signals passing through the mantle and the increasing capacity of computers to form images of mantle structure from these signals are sharpening seismologists' views to near the point of resolving the question. Already there are hints that mantle convection extends in one continuous roiling cauldron from the core to the bottom of the plates, although it does not appear to be as neatly laid out as textbook drawings would have it.

Seismic waves can produce a picture of the mantle because they pass through solid rock like light through water while being subtly affected by the variations of mantle properties from place to place. Hotter rock, perhaps the slowly rising arm of a convection cell carrying heat toward the surface, decreases the velocity of seismic waves while they are passing through it. Cooler rock, which may be downward convecting mantle or perhaps a slab of cold ocean plate sinking beneath a deep-sea trench, transmits seismic waves faster.

Seismologists have used these velocity variations to create the first three-dimensional images of the entire mantle. Two groups, Robert Clayton and colleagues at the California Institute of Technology and Adam Dziewonski of Harvard University, have mapped the variation of seismic velocity through the lower mantle from the core-mantle boundary to a depth of less than 700 kilometers. A sharp change in seismic properties at a depth of about 670 kilometers has been suggested by some as an impenetrable boundary between separate upper and lower convection systems. Coincidentally, the waves that these researchers must use to reach the deepest mantle, called body waves, become increasingly inappropriate for imaging above this depth. In order to map the upper mantle, two other groups, Ichiro Nakanishi and Don Anderson of Caltech and John Woodhouse of Harvard and Dziewonski, analyzed surface waves, which travel at the surface somewhat like waves on the surface of the sea and probe to varying depths, depending on their wavelengths.

The resulting images of the mantle look familiar near the surface but have some odder aspects at greater depths. As expected, in areas where magma from the mantle reaches the surface—at mid-ocean ridges and volcanic regions—high temperatures slow seismic waves at depths of about 100 kilometers. Immediately below long-stable, cooler continental regions like central Canada, velocities are higher.

But deeper, at 350 kilometers, the clear relation to crustal features appears to break down. The slow, hot anomalies beneath mid-ocean ridges are not continuous, and some ridge sections, such as the central mid-Atlantic, are actually underlain by fast, cooler mantle. The slow anomaly beneath the East Pacific Rise is largely absent or offset laterally at this depth; this suggested to Anderson and Dziewonski that ridges can be fed magma from the side rather than from directly below. The slow anomaly beneath the Afar Triangle of Northeast Africa, where rifting of the continent is forming a new ocean basin, does penetrate this deep. At 550 kilometers, the two main features—large fast regions under most of the South Atlantic and South America and under the western Pacific—may represent cold subducted rock, suggest Anderson and Dziewonski.

Deeper still, in the lower mantle, velocity variations are concentrated near the 700-kilometer level and near the core-mantle boundary. Clayton, among others, sees anomalies that apparently extend into the transition zone between the upper and lower mantle and down to the core. Some hot spots, volcanic centers such as Iceland or Hawaii that tap the mantle for magma, seem to have hot roots extending well into the lower mantle, says Clayton. In fact, Bradford Hager and Mark Richards of Caltech have found that on a broad scale the lower mantle shows a strong tendency to be hotter beneath hot spots. Some features detected by surface-wave studies in the upper mantle appear to be continuous with features detected by body-wave studies in the lower mantle. Vertically continuous features and correlations between lower mantle features and the surface, if real, would support the contention that the mantle convects as a whole, not in two separate layers as has been suggested by some.

Seismologists are now wondering just how much of this mantle structure they should believe. Not all the appropriate studies of the reliability and the resolving power of seismic mapping, especially of vertical resolution, have been completed, and many researchers remain skeptical of the reality of some features. But many seismologists are encouraged by several favorable indicators. For one, surface-wave studies do generate shallow velocity anomalies that make geological sense—mid-ocean ridges are not anomalously cold, for example.

Another encouraging aspect is the similarity of features, especially in the lower mantle, as seen in studies employing different imaging techniques. For the body-wave map of the lower mantle, Clayton used a mathematical technique like that of computerized axial tomography (CAT) scanning, in which an image of a slice of the human brain can be constructed from x-rays passed through it.

In the seismological application of tomography, the "x-ray" sources are large earthquakes and the detectors are seismographs in the worldwide network. For analysis, the mantle is divided into regular subdivisions or cells. If a seismic wave's travel time along a ray path connecting a source and a receiver were slower or faster than predicted by a standard, layered velocity model of the earth, the wave's travel time anomaly could be apportioned to each of the mantle cells through which the wave had passed.

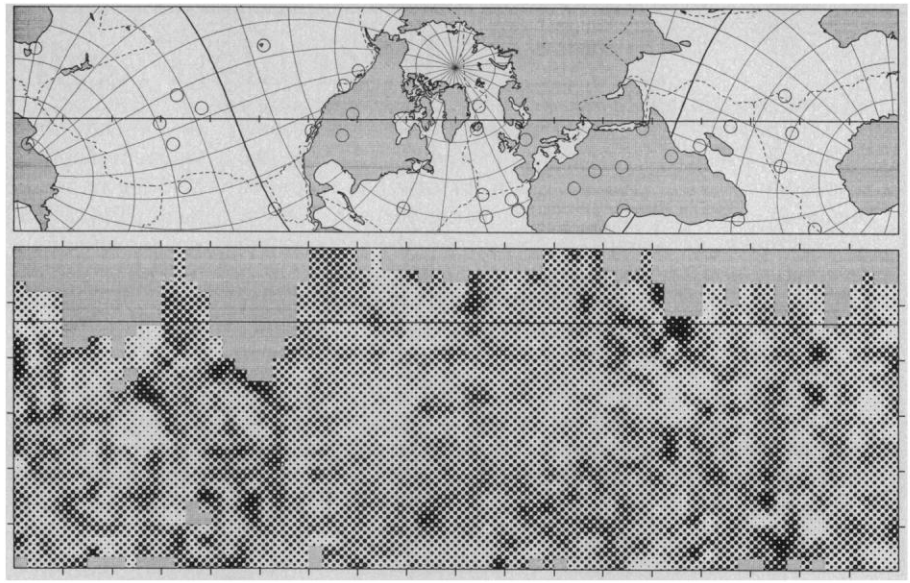
In order to determine just where along a ray the anomaly actually lies, many ray paths, in Clayton's study almost 2 million, are crisscrossed through the mantle. Rays anomalous in the same sense build up velocity anomalies where they cross and elsewhere tend to cancel anomalous rays of the opposite sense. Instead of subdividing the mantle into cells, Dziewonski described the same data in terms of spherical harmonics, the prescribed superposition of sine and cosine waves in such a way as to reproduce irregular signals.

Despite the use of different analyses, the two maps of the lower mantle agree rather well but only on the largest scales of 5,000 to 10,000 kilometers. In turn, however, the large-scale features common to both maps match features in an earlier seismic study and in the earth's gravity field. Hager and colleagues at Caltech have converted the observed large-scale velocity anomaly pattern into a pattern of density variations and compared their effect on the gravity field with the observed field.

After allowing for the effects of mantle motions, the calculated effect of the density variations accounted for more than 80 percent of the variations in gravity that had been unexplained. Apparently, both gravity measurements (which cannot provide depth information) and the two methods of analyzing seismic waves are detecting the same temperature variations (about 100°C). It is this pattern of variation that has been associated with a mantle convection cell on the scale of an entire hemisphere.

Attempts at directly calculating map resolution, although as yet not totally rigorous, are also encouraging. Clayton has inserted a known anomaly into an otherwise horizontally homogeneous model of the mantle, intersected it with typical ray path coverage, and regenerated the anomaly from these synthetic data. He is "quite confident" now that anomalies in authentic data are real. Toshiro Tanimoto of Caltech and Anderson have calculated a horizontal resolution of a few thousand kilometers in the upper mantle, good enough to detect an anomaly the size of India. Anderson estimates that the vertical resolution in the upper mantle is only 100 to 200 kilometers, depending on the depth.

One way to increase resolution is to forgo creating a global map while retaining the techniques needed for processing large amounts of data. Eugene Humphreys of Caltech, Clayton, and Hager have done just that to take a closer look than ever before at the mantle up to 500 kilometers beneath southern California. They applied tomographic analysis to 10,000 ray paths from the 200 seismograph stations of the dense Southern California Array, the same network that keeps an eye on the San Andreas.



Looking down to the earth's core

The travel times of seismic waves from their earthquake sources to receivers have been combined to form this cross section of mantle seismic velocities that extends from the surface to the core. (Bottom) Fast velocities (whiter areas) represent colder rock, and slow velocities (darker areas) represent hotter rock. The horizontal line marks a depth of 670 kilometers, the conventional boundary between the upper and lower mantle. (Top) Where the cross section (horizontal line of map) intersects some hot spots (circles), such as Iceland, slow, hot anomalies extend through the upper mantle. Smooth gray is area of insufficient data. [*Robert Clayton and Robert Comer, Caltech*]

The Caltech group found a slablike anomaly of 3 percent higher velocities extending down 250 kilometers directly beneath the Transverse Ranges where the San Andreas jogs to the left just north of Los Angeles. Humphreys and Hager are suggesting that perhaps the driving force that pushed up the Transverse Ranges is not in the plates but in the mantle itself. The opening in far southern California of the Salton Trough, an incipient rift, would have disturbed the temperature regime of the mantle enough to set up a convection cell having downwelling of cold mantle beneath the Transverse Ranges. That in turn would have drawn the plates into the Transverse Ranges and formed the bend, they say.

Another means of getting the most out of the available mantle ray paths is to look at the effects of mantle properties other than temperature. As the mantle flows under the driving force of temperature differences, its mineral crystals should tend to align with each other along the direction of flow. The velocity of some seismic waves will then depend on whether they are traveling in the direction of flow and crystal alignment or across it.

The Caltech group of Henri-Claud Nataf, Nakanishi, and Anderson used the response to flow direction of two types of surface waves to map areas where flow is predominantly horizontal, that is, at the base or top of convection cells, or predominantly vertical, as at the edges of convection cells. At a depth of 250 kilometers, flow seems to be mostly vertical beneath most mid-ocean ridges where hot mantle rises toward the surface and at most subduction zones where cold uppermost mantle and crust sink. As suggested by seismic temperature mapping, the Afar Triangle rift appears to be an area of deep vertical motion.

Despite new ways of manipulating seismic data, the present resolution of global or regional maps is largely limited by the number, distribution, and quality of seismographs. Seismologists intend to change that. Some 50 research organizations have banded together to form the Incorporated Research Institutions for Seismology (IRIS). A primary objective of IRIS is the creation of an expanded, modern, worldwide seismograph network laid out for research like seismic mapping. A second network of 1000 portable instruments would allow regional mapping of the crust and upper mantle with a resolution of a few kilometers.

—**Richard A. Kerr**

Additional Readings

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3. T. Tanimoto and D. L. Anderson, *ibid.*, p. 287.
4. J. H. Woodhouse and A. M. Dziewonski, *J. Geophys. Res.* **89**, 5953 (1984).