# Continents at the Core-Mantle Boundary?

*Probing of the boundary between the rocky mantle and fluid core suggests a variability reminiscent of the crust we live on*

SOME of the most interesting things happen at boundaries. Ships float on the boundary between air and water. Life evolved to its highest level at the boundary between air and rock. The continents themselves formed at the rock-air boundary and stand above the sea because of the contrast between them and the denser rock of the mantle below.

Seismologists probing the boundary between the lower mantle and the still denser iron-alloy fluid core are finding that quite a bit may be going on at this, the earth's strongest discontinuity. For years they have been detecting seismic irregularities that could be caused by bumpiness on the core-mantle boundary, from hundreds of meters of relief over tens of kilometers to undulations a thousand kilometers long. For the first time the seismologists' view has expanded to take in the entire core, revealing apparent irregularities of continental scale and magnitude. By comparing the seismic results with independent measures of the shape of the core, researchers have found that undulations on the core-mantle boundary may not account for all of the seismic variability. Some of it may be due to variations in composition, as is the case in the crust. From above or below, debris may have collected between the core and the mantle as it has at the surface. If so, it has formed a geological refuse pile that creates some of the most variable "terrain" within the solid earth.

A key to imaging the vicinity of the core-mantle boundary has been amassing enough observations of seismic waves affected by that region to sort out the superimposed effects of other regions. Any seismic wave passing from an earthquake through the core-mantle boundary will have to pass first through the entire mantle on its way down. On its way up to a seismograph, it will pass through the fluid outer core, perhaps the solid inner core, and then the mantle again before reaching the other side of the world.

In an attempt to isolate the effect of the core-mantle boundary region alone, which is a difficult task at such depths, Kenneth Creager and Thomas Jordan of the Massachusetts Institute of Technology constructed an image from the travel times of waves along two different paths. One wave passes nearly vertically through the boundary, the outer core, and the inner core. The other spends proportionately more time in the lower mantle and uppermost outer core by approaching and leaving the outer core at a sharp angle while transiting it far from the inner core.

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Creager and Jordan found that they could construct a model of the inner earth in which the velocity of seismic waves near the core-mantle boundary varies by about $\pm 5\%$ from place to place around the core. Velocities of the waves that they chose to use are highest around the poles of the core and slowest near its equator. Differences in temperature, composition, or more likely both might produce such considerable velocity differences. One means of expressing the changes required by the observations is in terms of the displacement of the boundary between solid, rocky mantle and fluid iron-alloy core that is required to produce such a velocity difference. Less than halfway to the center of the earth, 2889 kilometers down, the boundary would have to be displaced as much as 8 kilometers upward and 8 kilometers downward. Andrea Morelli and Adam Dziewonski of Harvard University, using a similar inner core path and a deeper outer core path, have found a boundary displacement of $\pm 5$ kilometers.

Precisely locating the zone producing the velocity changes has been the subject of some debate, but Creager and Jordan doubt that the velocity differences could have been generated far from the boundary, although their observations actually favor the uppermost outer core. David Stevenson of the California Institute of Technology has recently pointed out that the outer core, which can flow as easily as water, cannot support the required heterogeneity. "You can't have significant lateral density variations in the outer core," he says, "especially in the uppermost outer core." And Creager and Jordan had corrected their velocities for the heterogeneity already found in the overlying mantle by others using other seismic waves. The heterogeneity, they conclude, must be at the boundary, just above it, or just below it.

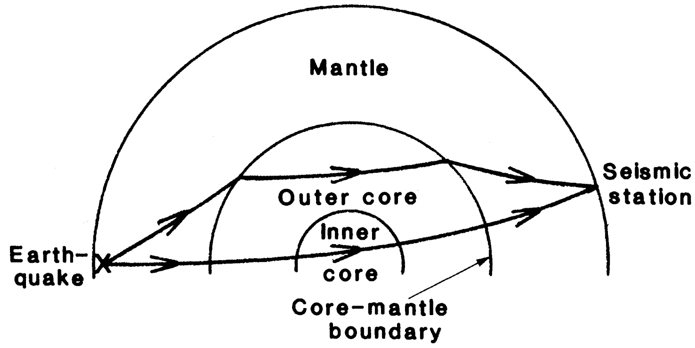
Rather than probing the inner earth by passing seismic waves through it, some seismologists are watching how earthquakes set the whole earth vibrating like a bell, revealing imperfections within. A perfectly formed spherical bell would produce a pure tone, but the rotation of the earth distorts its shape and creates additional tones in the whole-earth ringing set up by the largest earthquakes. The various modes of whole-earth vibration or free oscillation—such as twisting, ballooning, or elongating by a fraction of a millimeter over hundreds of seconds—differ in their sensitivity to imperfections at different locations within the earth. Thus, analysis of vibrations unaccounted for by rotation can locate additional imperfections.

Michael Ritzwoller, Guy Masters, and Freeman Gilbert of the University of California at San Diego analyzed a number of frequencies of free oscillations created by distortions of the earth's shape. The only location for the cause of anomalous frequencies that seemed consistent with the observations turned out to be the outer core. Like everyone else, Ritzwoller and his colleagues are reluctant to claim that the outer core can maintain such irregularities in its structure, which seem to be 100 times too strong for the fluid core to maintain. These researchers do note that the strength and pattern of their apparent outer core heterogeneity are similar to those implied by Creager and Jordan's travel time study, which also tends to place the heterogeneity in the outer core. Jordan, for one, would prefer to place it near the core-mantle boundary for the reasons already mentioned.

Domenico Giardini, Xiang-Dong Li, and John Woodhouse of Harvard University believe that their methods of analyzing anomalous free-oscillation frequencies can place the core heterogeneity where it will not offend any theorists. These Harvard researchers used oscillation modes that include one particularly sensitive to the zone a few kilometers inward of the core-mantle boundary. They place significant heterogeneity at the core-mantle boundary, at the inner core boundary, and within the inner core. They need place none in the outer core, says Woodhouse. The equivalent de-

**Seismic probes of the earth's interior**

*In attempts to detect whatever material may have collected near the core-mantle boundary, seismologists study earthquake-generated waves that follow different paths through the lowermost mantle and the core. The solid inner core plus the fluid outer core is the size of Mars.*




flection at the core-mantle boundary reaches 7.2 kilometers upward near the poles and the equator and 5.8 kilometers downward at middle latitudes.

Woodhouse suspects that the magnitudes of the heterogeneities found in the travel time observations cannot account for those that his group sees, that an unknown process is at work, but Jordan is more optimistic that the detailed comparisons yet to be made will reconcile the two approaches. Whatever the outcome, it would appear from the four sets of observations that the earth's deep interior, including the region near the core-mantle boundary, is highly variable on a scale of not just tens or hundreds of kilometers, as seen previously, but also thousands of kilometers.

Mounting evidence suggests that any large-scale heterogeneity of that magnitude cannot simply be undulations in the core-mantle boundary, but would include variations in composition of the mantle near the boundary—blobs of rock formed elsewhere that have settled there like scum collected between water and oil. The only way to maintain true boundary undulations is by the push and pull of the overlying mantle as it churns about carrying heat toward the surface through convective circulation. Two independent methods suggest that mantle dynamics cannot create undulations large enough to account for much of the apparent heterogeneity.

Bradford Hager and his colleagues at Caltech have used seismological and gravity observations related to the mantle to constrain the amount of deflection attributable to the core-mantle boundary. They inserted a three-dimensional map of denser, sinking regions of the mantle and less dense, rising regions, as determined by seismic studies, into a mathematical model of mantle flow. They then adjusted the viscosity of the model mantle until the given density distribution, combined with the model's deflection of the earth's surface due to mantle flow, produced the broad-scale variations in the gravity field observed at the surface. The model that explained 90% of the gravity field produced deflections in the core-mantle boundary of only ±2 kilometers, says Hager. This is less than the ±5 to 8 kilometers seen by seismologists, he notes, but it is still hard to say if there is a real difference, given the current uncertainties of the two new approaches.

A tighter constraint comes from measurements of the earth's wobble. Because the earth bulges at its equator as a result of its rotation, the sun and moon can tug on the earth as they orbit from one side of the equator to the other. That sets the earth wobbling or nutating, much the way a spinning gyroscope wobbles. If the shape of the core-mantle boundary deviates from its rotation-induced shape, the resulting tendency of the core and mantle to nutate out of step will show up particularly in the amplitude of a nutation having a period of 1 year.

Carl Gwinn, Thomas Herring, and Irwin Shapiro of the Harvard-Smithsonian Center for Astrophysics analyzed measurements of nutation made by very long baseline interferometry, a radio technique utilizing signals from far-distant quasars. The amplitudes of all the nutation periods matched theoretical predictions except the one particularly sensitive to the shape of the core-mantle boundary. Unable to find another cause of this milliarc-second deviation, Gwinn and his colleagues attribute it to a peak-to-valley undulation in the boundary of 490 ± 110 meters. The stated error is only in the observations, not the interpretation, but it would appear that this measure of the shape of the core-mantle boundary requires that seismologists attribute much of any real near-boundary heterogeneity to variations in composition.

Seismologists using a variety of seismic waves and techniques of analysis will now be trying to sort out the recent evidence of large-scale heterogeneity near the core-mantle boundary, much the way the blind men tried to work out the true nature of the elephant. But evidence from earlier studies involving different seismic waves, as well as geochemical and geophysical constraints, have already produced some ideas about what the lowermost mantle overlying the core is like. Called the D″ region, the lower couple hundred kilometers of the mantle has appeared to be exceptionally heterogeneous, as has the uppermost mantle most closely involved with crustal formation and continental drift. The rate of increase of seismic velocities with increasing depth also slows in D″. Velocities may even decrease with increasing depth there. Recently Thorne Lay of the University of Michigan and his colleagues have found evidence of a distinct upper boundary or lid to the D″ region.

One view of the vicinity of the core-mantle boundary and D″, offered by Geoffrey Davies of the Australian National University in Canberra before the latest seismic data appeared, places the region somewhere between the two possible extremes of complete isolation and active stirring throughout the lower mantle. Davies sees blobs of varying sizes and compositions in the lowermost mantle, some caught there in stable niches and others being swept up in rising plumes that could reach as far as the surface. These would be the plumes that supposedly create hot spots like Hawaii. Some of these blobs may have sunk from the upper mantle when ocean crust and mantle dove into deep-sea trenches, although they are destined to return to the surface as plumes after billions of years.

If the large-scale features appearing in seismic studies represent compositional heterogeneities, then they may be continent-sized blobs or clumps of blobs hugging the core that could act as storehouses of material awaiting recycling or ancient mantle material unchanged since the mantle formed. Jordan and Creager prefer that these continent-like masses have roots extending into the core that are stabilized by their particular combination of composition and temperature, in much the way surface continents are thought to act. In an even more speculative vein, the deflection of flow in the core by such blobs might provide the link required in some proposals between changes in the magnetic field generated in the core and volcanism at the surface. ■

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ADDITIONAL READING

Abstracts for the session on "Geophysics of the core and core-mantle boundary" at the spring meeting of the American Geophysics Union, *Eos* 67, 310 (1986).

M. Ritzwoller, G. Masters, F. Gilbert, "Observations of anomalous splitting and their interpretation in terms of aspherical structure," *J. Geophys. Res.*, in press.