Having It Both Ways in the Mantle

New evidence from the lab and the field is suggesting that advocates of a layered mantle and those favoring a mantle that mixes freely from top to bottom may both be partly right

When it comes to Earth's mantle—the layer of solid but mobile rock between the crust and the metallic core—there was once no room to sit on the fence. In one of the most contentious debates in geophysics, two vocal camps of researchers have long been arguing over the nature of a dividing line, 660 kilometers down in the mantle, that shows up in seismic studies of the deep earth. One camp sees this 660-kilometer boundary as a barrier separating the huge volume of mantle rock into two layers that never mix. An equally entrenched group argues that the boundary is no real obstacle to mantle mixing—it simply marks a place where pressure transforms the crystal structure of the rock—and the 2900-kilometer-deep mantle mixes from top to bottom like a pot of boiling water.

The dispute goes to the very heart of how the planet works—how the motions in its interior drive surface geology. If the layered-mantle view is correct, the rock of the lower mantle would be sealed off forever from contributing to continental drift and volcanoes, earthquakes, and mountain building. If the whole-mantle view holds, hot rock rising from as deep as the very edge of the molten core could be driving events at the surface. It's a stalemate of truly global proportions.

But now a middle ground is emerging. Nothing so strong as a consensus, it is more of a new focus on the possibility that the 660-kilometer boundary is a real barrier, but not an impermeable one; sometimes, at a few places, rock does cross the boundary. That's "a good working hypothesis for the moment," says mantle modeler Louise Kellogg of the University of California (UC), Davis, in the light of new results on several different fronts that, taken together, blur the old extremes. Efforts to create the minerals that exist at the high temperatures and pressures of the lower mantle suggest that, while different from the upper mantle, they aren't so different as to rule out the possibility that the two layers sometimes mix. Meanwhile, theoretical models of mantle behavior are suggesting how that mingling might take place. And glimpses of the real mantle seem to agree with the predictions: Seismic waves may be beginning to trace ghostly images of cold material—the remains of Earth's surface plates—diving through the disputed boundary.

That picture, adds Kellogg, "may not be as satisfying as whole-mantle convection or a layered mantle, but the earth is complicated, so it wouldn't be surprising if [mantle behavior] turns out to be complicated." And if this hybrid mantle concept were to prove out, there might be satisfaction enough to go around. Researchers who have argued for two separate layers could take comfort in the evidence that the 660-kilometer boundary has done its job well enough to keep the upper and lower mantles chemically distinct for more than 4 billion years. Those who have favored mixing throughout the mantle could claim partial vindication in the evidence that slabs of oceanic plate do plunge through the barrier, and plumes of hot rock may rise through it to form volcanic hot spots like Hawaii. Everybody might finally be happy.

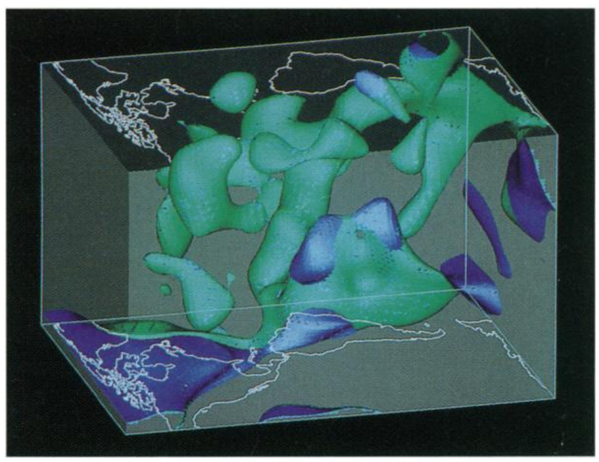
Flip, flop...and partial flip

Such a geophysical nirvana may yet slip from researchers' grasp, however, because some pivotal laboratory experiments—efforts to approach deep-mantle conditions—are notoriously tricky (*Science*, 29 November 1991, p. 1295). As the technology of the experiments has advanced, the evidence has flip-flopped more than once since pioneering work done 7 years ago.

An early foray into the analysis of deep-mantle minerals, at a time when geophysicists leaned toward complete mixing of the mantle, revitalized the double-layer scenario. Experimental mineralogists Elise Knittle, who is now at UC Santa Cruz, and Raymond Jeanloz of UC Berkeley synthesized samples of perovskite, the mantle's dominant mineral, at high temperature and pressure in a tiny diamond-anvil cell, and extrapolated their measurements of the perovskite's heat-induced expansion to deep-mantle conditions. Their conclusion: The expansion seemed so large that the lower mantle couldn't transmit seismic waves as observed—unless it has a different composition from the rock of the upper mantle. An enrichment in iron, they argued, would account for the seismic behavior. But if the lower mantle contained so much more iron than the upper mantle, the two layers must not have mixed significantly over Earth history. Nor would they have been able to: The addition of so much iron would make the rock of the lower mantle about 5% denser than upper mantle rock at similar temperature and pressures, segregating the two layers.

But there was plenty of room for doubt. For one thing, Knittle and Jeanloz had no way of directly measuring the mineral's properties under the high pressures and temperatures in their diamond-anvil cell. They had to remove the perovskite from the cell and extrapolate from measurements made at atmospheric pressure and a maximum temperature of 840 K—well short of the deep-mantle temperatures of 2000 K and above. Any hotter, and the unpressurized sample would decompose.

Five years later, the doubts seemed to be borne out by a flip back toward a well-mixed mantle. Yanbin Wang, Donald Weidner, and colleagues at the State University of New York at Stony Brook did the same experiment as Knittle and Jeanloz had performed, but with a difference (*Science*, 25 January 1991, p. 383). Wanting to push their sample closer to mantle conditions during their measurements, Wang and his colleagues repressurized their perovskite to shallow upper-mantle pressures in a massive press at Stony Brook. They managed to keep the material stable up to 1250 K. With that broader view, they concluded that Knittle and Jeanloz had been misled in their conclusions about thermal expansion by an abrupt jump—a phase transition—from one form of perovskite to another that came right at the upper end of their run. The lower mantle needs no iron enrichment to match seismic observations, the Stony Brook group concluded. The mantle need not be stratified.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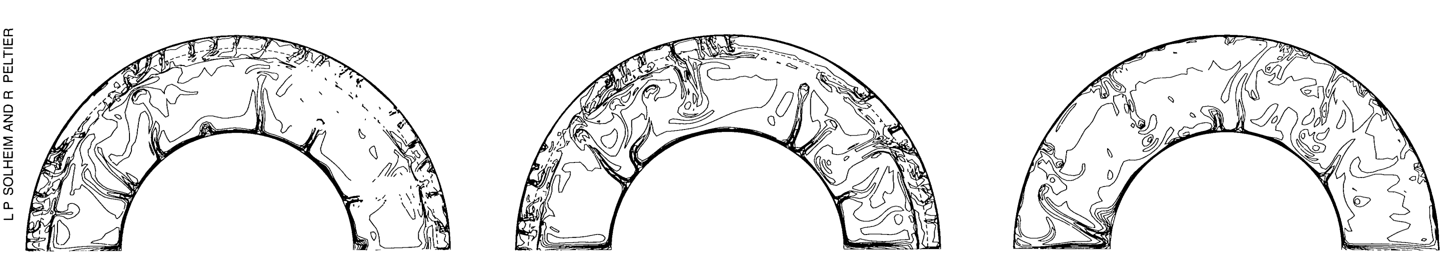
Deep penetration? Seismic imaging reveals relatively cold mantle rock, including a deep blob beneath South America.



L P SOLHEIM AND R PELTIER

Three portraits of the mantle. Computer simulations of mantle temperature portray mixing from top to bottom *(right)* in the absence of any barrier, but a phase-change barrier can enforce extreme layering *(left)* that occasionally breaks down *(center)*.

Now comes a flop in the other direction, propelled by the first measurements made under simultaneous high temperatures and high pressures—pressures typical of the shallowest parts of the lower mantle. This experimental first came from workers at the Carnegie Institution of Washington's Geophysical Laboratory. Ho Kwang Mao and colleagues studied perovskite at up to 23 gigapascals and 900 K, and Yingwei Fei and colleagues did the same for magnesiowüstite, the mantle's second most abundant mineral. The key was a technological first: The Carnegie groups used powerful synchrotron x-rays and an x-ray camera of their own design to study crystal structure while the minerals were still in the diamond cell.

From these measurements Carnegie researchers Lars Stixrude, who is now at the Georgia Institute of Technology, Russell Hemley, Mao, and Fei concluded in a recent paper in *Science* (21 August, p. 1099) that Knittle and Jeanloz were right—more or less. The Carnegie group didn't see the phase change reported by the Stony Brook researchers, who are themselves finding it difficult to reproduce. Instead the Carnegie workers conclude that the lower mantle is enriched in heavier elements, probably silica and perhaps iron. And that means that instead of a well-mixed, single-layer mantle, says Stixrude, "It's a pretty secure conclusion that the mantle convects in two layers."

But the pendulum hasn't swung all the way back to a permanently stratified mantle, Stixrude and Hemley emphasize: "A compositional change near 660 kilometers is consistent with the most recent data," says Hemley, "but the change is probably not that large. It may be the [resulting] density difference is on the order of a few percent"—less than the 5% Jeanloz had calculated and far less than the 10% layered-mantle advocates talked of 10 years ago. "Even while the evidence for stratification is accumulating," notes Peter Olson of Johns Hopkins University, who runs computer models of mantle behavior, "the magnitude of the [density] difference is becoming smaller."

A sinking hypothesis

That incremental change is helping bring about a shift in attitude toward the workings of the mantle. While a density difference of 5% or more would likely enforce a permanent and absolute segregation of the upper and lower mantle, a density difference of 1% to 2% "doesn't preclude some mixing," says Hemley. The most likely agents of mixing are the slabs of old, cold, and therefore dense, oceanic plate that sink into the mantle at deep-sea trenches. They would have the best chance of puncturing the 660-kilometer barrier at the top of the denser lower mantle. Says Hemley, "At some places there may be penetration of slabs but at other points there may be what looks like two-layer convection."

Theoretical calculations give some hints about how such a half-mixed mantle might work. In 1988, with seismologist Paul Silver and geochemist Richard Carlson of Carnegie, Olson proposed a model in which the lower mantle was only slightly denser than the upper mantle. Slabs could easily slip through the 660-kilometer barrier, the trio found—but they didn't stay there. After 100 million years or so of heating, their slight compositional difference would make the slabs buoyant. Providing the slabs bobbed back up before they mixed into the lower mantle, the two layers could maintain their separate identities.

Alternatively, say other researchers, only a few slabs might make it past the 660-kilometer boundary in the first place. The small compositional difference indicated by the latest mineral experiments might not be enough to hold back most slabs. But mantle modelers are finding that the change in the mantle rock's crystal structure to a denser form at 660 kilometers can beef up the barrier.

Advocates of whole-mantle mixing had thought this phase change wouldn't stop material from mixing across the boundary because a shallower phase change, at 400 kilometers, would cancel out its effect, but mantle modelers Larry P. Solheim and Richard Peltier of the University of Toronto have found that the deeper one might help raise a barrier after all. They created a mantle model with no compositional differences, only the two phase changes. The relatively low temperature of a descending slab, they found, delayed the deeper phase change even after the slab passed 660 kilometers, keeping the material less dense than the lower mantle and stopping its descent. Still, the barrier wasn't unbreachable, says Solheim. Eventually upper mantle rock became so cold and dense and the lower mantle so hot and buoyant that at some places the phase-change barrier was overwhelmed, allowing the two layers of the model mantle to mix temporarily.

Glimpses from the real world

The ultimate test of these ideas is the behavior of real slabs, something only now beginning to be glimpsed with any clarity. For more than a decade seismologists have been analyzing seismic waves passing beneath deep-sea trenches, looking for evidence—in the form of altered seismic velocities—that cold, dense slabs have dipped below the 660-kilometer boundary. Interpretations of such seismic slab imaging have been controversial (*Science*, 24 May 1991, p. 1069), but there is now general agreement on a couple of points. For one, whatever combination of compositional differences and phase changes creates the 660-kilometer boundary, it presents a considerable obstacle. No slab encounters it without paying a price. In the western Pacific, some slabs seem to crumple without penetrating, and others bend to slide along the boundary for as much as 1000 kilometers.

But many seismologists are now seeing signs of slab penetration at other places in the western Pacific. For example, Yoshio Fukao and his colleagues at Nagoya University have reported that slabs beneath Indonesia's Java Trench and the Kurile Trench northeast of Japan appear to penetrate to a depth of 1200 kilometers. And Rob van der Hilst of the University of Leeds has found evidence of penetration beneath the Marianas Trench south of Japan and under the northern but not the southern Kurile Trench.

Appearances can be deceptive, of course, as attendees at the May meeting of the American Geophysical Union in Montreal were reminded in a session on mantle structure. Most of the geophysicists were taking the reports at face value until seismologist Don L. Anderson of the California Institute of Technology stood to question a speaker. Anderson, a staunch advocate of permanent mantle stratification, pointed out another equally valid interpretation of the seismic observations. Rather than piercing the boundary, a cold slab could soak up heat from the rock on the other side of the boundary, giving the impression in temperature-dependent seismic images of one continuous cold slab diving into the lower mantle.

Since then, seismologists have been trying to pin down the difference between heat conduction and a real slab. Stephen Grand of the University of Texas, Austin, for instance, points to his new seismic images, which show lower mantle features that he thinks look more like slabs than anything else. In a regional study of the eastern margin of the Pacific, where as much as 5000 kilometers of ocean plate has sunk into the mantle during the past 50 million years, Grand finds a thick wedge of cold rock that, below a depth of 660 kilometers, extends more than 500 kilometers horizontally under South America and North America. "My personal belief is that that's slab material in the lower mantle," says Grand. "[Anderson] could be right, but I'd like someone to explain to me how you get that without penetration."

To resolve such doubts, all three bands of researchers studying the workings of the mantle are trying to get closer to the real thing. Mineral physicists hope eventually to duplicate deep-mantle conditions so that they no longer have to extrapolate from what happens at milder conditions. Modelers are constantly increasing the realism of their simulations. But perhaps most crucially, seismologists are gaining on their goal of a complete worldwide network of the latest in seismographs, or "full-fidelity earthquake recorders," as David Simpson of the Incorporated Research Institutions for Seismology (IRIS) in Arlington, Virginia, describes them. These machines digitally record seismic waves at frequencies from 10 hertz to thousands of hertz without chopping off the highest-amplitude waves, unlike the 1960s-vintage instruments they are replacing. "It's the difference between a 78 rpm record and a CD," says Simpson.

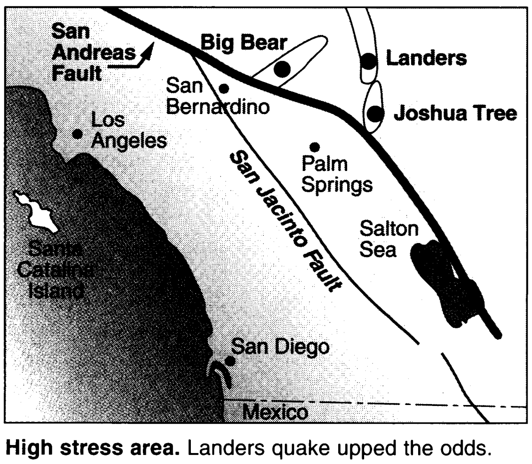
IRIS has installed about 65 of these broadband digital instruments around the world and hopes to double that number; meanwhile, other countries are contributing stations as well. Once coverage is fairly even across both land and sea, seismologists should be able to paint a detailed picture of inner Earth that will not be open to artistic interpretation.

–Richard A. Kerr

SEISMOLOGY

Quake Heightens Concern, Uncertainty

A panel of seismologists reported this week that the Landers earthquake—a magnitude 7.5 temblor that shook a thinly populated desert area 105 kilometers east of Los Angeles in June—has made it more likely that another big one will soon strike Southern California. But the panel is unable to say just how much the risks have increased. Its best guess is that the chances of a temblor larger than magnitude 7 striking the Landers area in the year starting last September have increased by a factor of between two and five, and the probability of such a quake in Southern California as a whole has risen between 25% and a factor of 3. The panel's worst-case estimate is that Southern Californians have a one-in-eight chance of experiencing a magnitude 7 quake by next September.



High stress area. Landers quake upped the odds.

These wide ranges of probabilities reflect uncertainties among seismologists themselves about how earthquakes should be forecasted. "There are problems both with the statistical techniques and with our understanding of the physics of earthquakes," says seismologist Thomas Heaton of the U.S. Geological Survey in Pasadena, cochair of the panel.* "We're arguing over what actually goes on in an earthquake."

The first thing the working group did was to question the conventional method of estimating when a fault is next going to fail in a large quake. Used in 1988 to estimate the hazards on the San Andreas fault system throughout California (*Science*, 22 July 1988, p. 413), that method assumed that a specific section of the San Andreas would gradually accumulate stress, reach the breaking point, and rupture, releasing the accumulated stress in an earthquake. The cycle would then repeat to give a series of similar quakes at roughly equal intervals. Seismologists simply forecasted the probability of the next quake from the date and size of the last one and the rate of stress accumulation. But when researchers calculated that the Landers quake transferred enough stress to the adjacent segment of the San Andreas to advance the date of its next rupture by a decade or two (see reports in *Science*, 20 November), the calculated probability of the next magnitude 7 on the San Andreas increased by a meaninglessly small amount. This anomalous result only served to point up the limitations of the technique when forecasts are uncertain by decades.

The panel also decided that the focus of the 1988 report was too narrow: "It's deceptive to focus only on the San Andreas, and only certain segments of it, when in fact there are lots of faults in Southern California," says Heaton. So the panel turned to alternative forecasting techniques and applied them more broadly. The new techniques all involved searching catalogs of past earthquakes to find some that might say something about the possibility of future quakes.

In one approach, panel members asked how often large earthquakes come in pairs. The worldwide record suggested about a 3% chance that the Landers quake would be paired with a similar shock in the vicinity within 2 to 14 months. If quakes were random events with no pairing, the odds would be only 1%. But no one is sure whether California quakes follow the global pattern. Similar uncertainties underlie the estimates for Southern California as a whole. According to one calculation, for example, if the increased frequency of moderate earthquakes seen in the region since 1985 continues, the odds of a magnitude 7 temblor striking there by next September would be 12%—three times greater than if the frequency had not changed. But no one knows whether the recent surge in seismicity will persist.

And the uncertainties would get even worse if the views of David Jackson, a working group member, and Yan Kagan of the University of California, Los Angeles, become widely accepted. Jackson and Kagan argue that faults remain stressed near their breaking point even after being ruptured in a large quake, so that they can soon break again. After a cluster of quakes on the same fault, they say, it can somehow be deactivated for long periods. Thus, Kagan and Jackson would regard a long-quiet fault that others assume to be overdue for another large quake as only a slight threat. Applying this reasoning to Southern California gives a probability increase of only one-third for the region as a whole and less than 50% for the Landers neighborhood. "Dave Jackson's objections are ones we have to deal with," acknowledges Heaton. But that, he says, will have to await the working group's next report, due out after Southern Californians have lived with another 9 months of increased uncertainty.

–Richard A. Kerr

*The Working Group on the Probabilities of Future Large Earthquakes in Southern California is composed of individuals from the national and the California earthquake prediction evaluation councils and the Southern California Earthquake Center.