A Low-Iron Recipe for Deep-Mantle Rock

The latest lab effort to probe deep-Earth conditions hints that the mantle mixes throughout its 2900-kilometer depth

THE MOST BEDEVILING CONTROVERSY IN geophysics may be the question of Earth's deep structure. Is the mantle formed, as some geophysicists think, of two distinct layers that never mix? Or does the mantle roil from top to bottom much like water boiling in a pot? On the answer hinges a better understanding of how Earth's heat-driven engine works, the topmost part of which is plate tectonics.

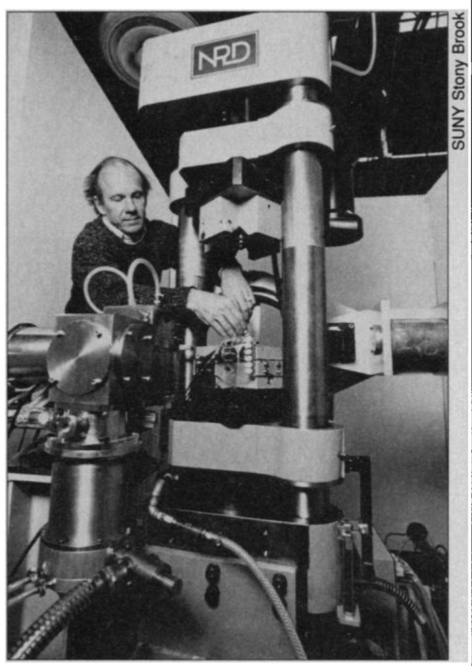
Now, on page 410 of this issue of *Science*, Yanbin Wang and his colleagues at the State University of New York at Stony Brook report the results of a new lab experiment that comes down on the side of a well-mixed mantle. "People are very excited," says crystallographer Russell Hemley, who has been doing similar work at the Geophysical Laboratory in Washington, D.C. If the Wang group is correct, it would mean that the lower mantle exchanges both heat and rock with the upper mantle and ultimately Earth's surface. The deepest mantle could, for example, send plumes to the surface to form volcanic hot spots, and the turmoil of drifting continents and sinking tectonic plates could, in turn, penetrate all the way into the lower mantle, more than 2000 kilometers below the surface.

Hemley adds, however, that researchers are treating the Stony Brook group's results with caution, primarily because they have not yet been reproduced. Nevertheless, the new work is impressing many researchers, especially those who have visited the Stony Brook lab. "Although it is only one determination," says one such visitor, experimental mineralogist William Bassett of Cornell University, "I find their arguments quite convincing."

Understanding mantle structure has been such a bugaboo because it depends on knowing the behavior of minerals that in nature exist only beneath 700 kilometers of rock. So researchers who want to understand how the deep Earth behaves have to try to recreate its high temperatures and pressures within powerful presses.

One of the preeminent practitioners of this art is Raymond Jeanloz of the University of California, Berkeley (*Science*, 10 November 1989, p. 758). About 5 years ago, work by his group suggested that perovskite, the dominant mineral of the mantle, is enriched in iron compared to the minerals of the upper mantle. Because any significant mixing over the eons between the two layers should have wiped out such an enrichment, Jeanloz concluded that there had been no such mixing.

The experiment performed by Wang and his colleagues is a new version of the Jeanloz experiment that leads them to just the opposite conclusion. Both groups began by transforming a sample of ordinary silicate into perovskite by squeezing and heating it to temperatures and pressures—about 2000 K and 30 gigapascals—typical of those at the top of the lower mantle 800 kilometers down. That treatment reorders the sample's crystal structure, giving it the distorted cubic structure of a perovskite.



A crucial squeeze. *This high-pressure press saved the sample and the day.*

But after the two groups of researchers created their mantle mineral samples, they faced a potentially fatal problem. At present it is impossible to equip the high-temperature, high-pressure presses with instruments to measure perovskite's properties directly. The obvious alternative is to return the perovskite to room temperature and pressure, make the measurements, and extrapolate the results back to deep mantle conditions. The catch is that the two groups needed to measure perovskite's expansion with increasing temperature in order to extrapolate to its mantle density and composition, but the mineral decomposes when heated much more than a few hundred degrees at room pressure.

The Berkeley researchers did the best they could. Elise Knittle, who has since moved to UC, Santa Cruz, Jeanloz, and Gordon Smith of Lawrence Livermore National Laboratory managed to heat one sample of perovskite from 300 K to 840 K, just below the temperature where it would have decomposed at room pressure. From that experiment, they concluded that perovskite's thermal expansion is exceptionally large. That led them to deduce that the lower mantle must be enriched in iron—18% iron rather than the conventionally accepted 10%—in order for the density of perovskite to match the density of the lower mantle as determined by seismic studies.

Although the Berkeley group's experiment was an impressive achievement in its day, Wang and his colleagues made several improvements in the determination of thermal expansion that may have accounted for their different result. Perhaps most important, they were able to measure the expansion of perovskite over a broader temperature range. They did this by repressurizing their sample in a press to 7.3 gigapascals—well below deep-Earth pressures but high enough to slow perovskite decomposition to the point that measurements could be made up to 1250 K, rather than to 840 K. "If we did not have that," says Donald Weidner of the Stony Brook group, "we could have come to the same conclusion as Knittle and Jeanloz."

Because they took their measurements to higher temperatures, the Stony Brook workers were able to see something the Berkeley workers apparently missed. The perovskite expanded gradually with increasing temperature to about 600 K, where the expansion suddenly jumped. After that, the rate of expansion was about what it had been before. Stony Brook workers attribute the jump at 600 K to a phase transition in which the crystal structure abruptly becomes slightly distorted.

The Berkeley researchers did not recognize this phase transition, Weidner suggests, because they had to stop just above it, before the resumption of modest expansion could become obvious. Also, the Berkeley measurement errors were twice as large as Stony Brook's. Thus, in the Stony Brook view, the unrecognized phase transition made it appear that perovskite expands rapidly, leading the Berkeley workers to conclude unnecessarily that the lower mantle is iron-rich and unmixed. Since the gradual expansion observed by the Stony Brook group would in the long

Stiffening Up the Lower Mantle

It's always nice when two different types of experiments point toward the same conclusion, particularly when they might help settle a long-running controversy. For a decade and more, geophysicists have argued whether Earth's mantle forms distinct stratified layers that never mix. Now a new estimate of the stiffness of mantle rock supports the idea of a mantle that mixes from top to bottom, a view also bolstered by new results from researchers using high-pressure presses to simulate deep mantle conditions (see main story).

Geophysicists trying to estimate the stiffness or viscosity of the mantle have traditionally been a fractious lot, but in recent years many of them have agreed that viscosity doesn't change much from the top of the mantle to its bottom. For example, Richard Peltier and Jerry X. Mitrovica of the University of Toronto recently concluded that the viscosity increases between two- and fourfold between the upper and lower mantle, a modest change by geophysical standards. The Toronto workers arrived at that gradient by analyzing how the crust and mantle beneath Hudson Bay bounced back from being depressed by the enormous burden of the ice sheet that melted 10,000 years ago.

Something deep within Earth obstructs falling slabs. Is it a highly viscous lower mantle?

A mantle with relatively uniform viscosity may be fine with many experts in postglacial rebound studies, but it presents a problem for anyone who believes the mantle mixes from top to bottom. Seismic images show that slabs of old tectonic plate sinking through the upper mantle compress and shorten about 670 kilometers down—just as if they are running into something. Researchers who favor a permanently stratified mantle say the slabs are hitting a dense, iron-rich mantle that doesn't mix, even with slabs. Those who favor whole mantle mixing, however, think that rock compositions should be similar on both sides of the 670-kilometer boundary. They need some other sort of obstacle that would offer resistance to the slabs while still allowing mixing. Unfortunately for them, a modest fourfold viscosity increase between the upper and lower mantle wouldn't put up enough resistance to distort descending slabs.

Enter geophysicist Bradford Hager of the Massachusetts Institute of Technology. By estimating mantle viscosity three different ways and combining the results, he's come up with a 30-fold, rather than a fourfold, difference between the upper and lower mantle. That, he says, should be enough to make the lower mantle a stiff, resistive obstacle, while still allowing some mixing.

All three of Hager's estimates are based on geophysical changes brought about by the ponderously slow flow of the mantle over millions of years, rather than the sharp snap of glacial rebound. One of these calculations, performed with Robert Clayton of the California Institute of Technology, takes as its starting point the amount of heat that the lower mantle transports to Earth's surface. Because that transport occurs by convection, the same means by which a building thunderhead cloud carries heat upwards, it should be influenced by the viscosity of the convecting material, Hager and Clayton reasoned. So the amount of heat reaching Earth's surface from the mantle—known to be about 30 terrawatts—allowed Hager and Clayton to put limits on the viscosity of the lower mantle; if it were too fluid, its convection would carry more heat than is seen, and if it were too stiff, not enough heat would reach the surface.

In his second calculation, Hager and Richard O'Connell of Harvard University determined limits on viscosity from the speed of tectonic plates as they slide across the top of the mantle at some centimeters per year. If the underlying mantle were too stiff, the reasoning goes, the circulation set up in the mantle by plate motion would slow the plates below their known speeds.

In the third calculation, Hager, Clayton, and Mark Richards of the University of California, Berkeley, drew on three-dimensional images of the mantle produced by a technique called seismic tomography. Based on the same principles as x-ray CAT scanning of the human body, seismic tomography maps out blobs of mantle that are more dense than average, such as the cold slabs, and zones that are less dense than average, such as the hot mantle underlying the volcanic mid-ocean ridges. Blobs sinking or rising through the mantle create telltale variations in the pull of gravity at the surface that are related to the viscosity of the fluid through which the blobs are moving. Hager and his colleagues analyzed these variations to derive the change of viscosity with depth.

Hager believes that most of the difference between his results and those obtained by the glacial rebound method can be attributed to geographical variations in upper mantle viscosity. The viscosities he's determined are more representative of those beneath the oceans, he says. But glacial rebound has been measured mainly over land where the upper mantle is likely to be colder, and therefore stiffer, than the mantle beneath the oceans. That would tend to make gradients determined by glacial rebound less steep.

If Hager is right, a second puzzling geophysical observation would also be explained. Some mantle-derived rocks found at the surface show few geochemical signs of mixing with the rest of the mantle for a billion years or more. A highly viscous, sluggishly circulating lower mantle would be just the place to store such rocks for a while before finally driving them upward. ■ **R.A.K.**

run dominate any effect of the phase transition, Wang and his colleagues see no need for iron enrichment.

Although Jeanloz, like a number of other researchers, is intrigued by the Stony Brook results, he is not yet ready to give up on his own ideas about the lower mantle. "The result is tantalizing," he says. "I have no a priori reason to think it's wrong," but the lack of some kind of confirmation leaves him uneasy. In his group's experiment, the perovskite's volume was measured as the sample was heated and also as it cooled and contracted in order to make sure its behavior had not been altered by the high temperatures. The Stony Brook group did not do that. They have not yet even repeated the one-way experiment because the transition only became apparent in their data a month after they had to relinquish their slot at the National Synchrotron Light Source, the source of the high-intensity x-rays that they use to measure perovskite expansion.

In defense of their single-experiment results, Weidner notes that several other aspects of their data also suggest a phase transition. For example, x-ray diffraction data show that the perovskite structure is slightly different above 600 K. Weidner recognizes the need for more experiments, which will resume next month when they get more time at the synchrotron. "The experiments have only begun," he notes. ■ **RICHARD A. KERR**