Putting Stiffness in Earth's Mantle

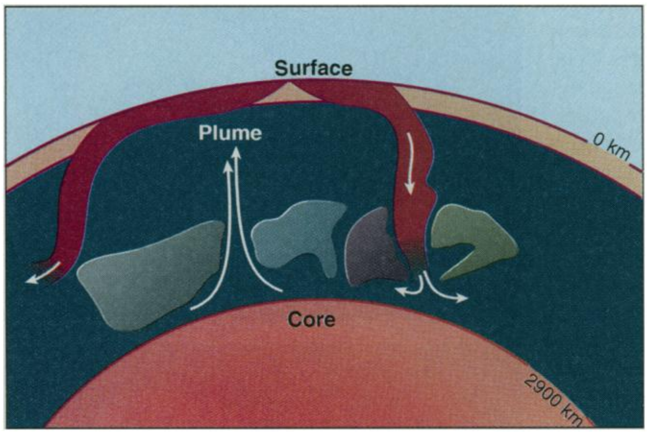
After a decade of contention, geophysicists now agree that the deepest rocks are exceptionally stiff, opening the way toward a unified view of Earth's deep interior

To geophysicists, the Earth's deep interior is more like molasses than marble. The mantle rock that fills Earth between its thin tectonic plates and the molten-iron core 2900 kilometers below may seem solid enough, but over geologic time, the high temperatures of the mantle make the rock soft enough to flow. Just how soft it is, however, is an issue that has bitterly divided the geophysical community over the last decade.

One camp has held that the viscosity stays relatively constant all the way to the core, as the increase in temperature with depth more or less balances the stiffening effects of increasing pressure. The other argues that the stiffness of the rock soars in the deep mantle, increasing by a factor of 30 or so as the rock compresses and assumes new crystal structures at greater depths. A resolution could help settle the most contentious issue about the deep Earth: Does the mantle mix thoroughly from top to bottom, as hints that surface rocks can descend into the deep mantle imply? Or is the lower mantle sealed off from the upper mantle, as is suggested by the composition of some surface rocks? Now there's new hope that this split in the mantle—and the geophysics community—can be healed.

In a study published last month and another in press, geophysicists Jerry X. Mitrovica of the University of Toronto and Alessandro Forte of the Earth Physics Institute in Paris have taken a closer look at two traditional indicators of mantle viscosity—slight variations in the force of gravity over Earth's surface and the rebound of land areas since they were relieved of the weight of ice after the last glaciation. In the past, those indicators have given incompatible results, but Mitrovica and Forte have found that they can be reconciled in a picture of mantle viscosity that increases markedly from top to bottom, perhaps by an even larger factor than had been thought. The new work, says mantle modeler Michael Gurnis of the California Institute of Technology, "is such a breath of fresh air."

And so is one of its immediate consequences, say other geophysicists: a picture of Earth's interior that uses the very stiff lower mantle confirmed by the new result to strike a middle ground between whole-mantle and layered mixing. This new description of mantle motions, put forward by geophysicist Richard O'Connell of Harvard University, holds that some parts of the lower mantle do mix slowly with shallower ones, but the high viscosity allows others to stay segregated for hundreds of millions or even billions of years as deep blobs of highly viscous material. "It's my favorite model," says Thomas Jordan of the Massachusetts Institute of Technology (MIT), who has been a staunch advocate of whole-mantle mixing. "It begins to split the difference between models. There are still a lot of questions, but it's beginning to make sense."



SOURCE: M. MANGA

Something for everyone. A new picture of the mantle allows plumes and descending slabs to penetrate the lower mantle but keeps other parts isolated as "blobs."

Squishy viscosity

For many years now, the viscosity of the mantle hasn't made a lot of sense, to judge from the dueling papers in the field. On one side were those who analyzed the subtle variations of gravity across Earth's surface. Regions of the mantle that have higher densities than average, for example, are sinking. They tend to change the pull of gravity at the surface by their high density as well as by dimpling the surface as they sink, like pebbles dropped in molasses—an effect that depends on the viscosity of the mantle. By combining the observed gravity variations with the mantle density variations revealed in seismic images, which are computed from the behavior of deep-diving seismic waves, Bradford Hager of MIT and his colleagues found that the lower mantle must be something like 30 times more viscous than the upper mantle (*Science*, 25 January 1991, p. 383). That would slow mixing between the upper and lower mantle or prevent it altogether.

A whole community of geophysicists, drawing on a half century of study, rejected that conclusion, however. They argued that viscosity increases only modestly with increasing depth. Their evidence came from differences in the rate at which land weighted down by ice sheets of different sizes during the last ice age is rebounding. They concluded that the viscosity contrast wasn't much more than a factor of 2 to 4. That wouldn't do much to keep the upper and lower mantle separate.

But when Mitrovica did some historical research, he found that inferences from glacial rebound and from gravity studies "are not incompatible at all." The problem, he found, lay in the use researchers were making of a classic study of viscosity in the shallow mantle done in 1935 and 1936 by the late geophysicist Norman Haskell of MIT. Haskell had studied the rate at which Scandinavia has been rising since the Fennoscandian ice sheet retreated more than 10,000 years ago. Mitrovica reanalyzed a key rebound record from Norway and confirmed that "Haskell was right"—but latter-day researchers had been applying his numbers to the wrong part of the mantle.

In using Haskell's result to calculate the viscosity of the mantle, researchers in the 1980s had focused on the 660-kilometer boundary, where mineral physicists showed in the 1960s that increasing pressure transforms the crystal structure of the mantle rock. The 660-kilometer boundary seemed a natural cutoff for Haskell's viscosity number. To probe deeper parts of the mantle, they used more recent studies of rebound from a larger ice sheet, like North America's Laurentide.

But Mitrovica found that Haskell's data "tell you the average viscosity down to 1400 kilometers, not down to 660 kilometers." By applying a number relevant to the entire upper half of the mantle to just its uppermost quarter, researchers had skewed their estimates of the increase of viscosity with depth to the low side, says Mitrovica: "The old idea that glacial rebound requires a viscosity that does not increase with depth is wrong."

To pin down what the increase might be from top to bottom in the mantle, Mitrovica and Forte have recently combined rebound and gravity data into a single calculation of viscosity variation with depth. They found that the combined data set points to an overall 80- to 100-fold increase in viscosity through the mantle, with the sharpest jumps at around 660 kilometers and 1100 kilometers. That is higher than Hager's factor of 30, but given the uncertainties of the data both analyses fall in the stiff lower mantle camp and well above the traditional glacial rebound result.

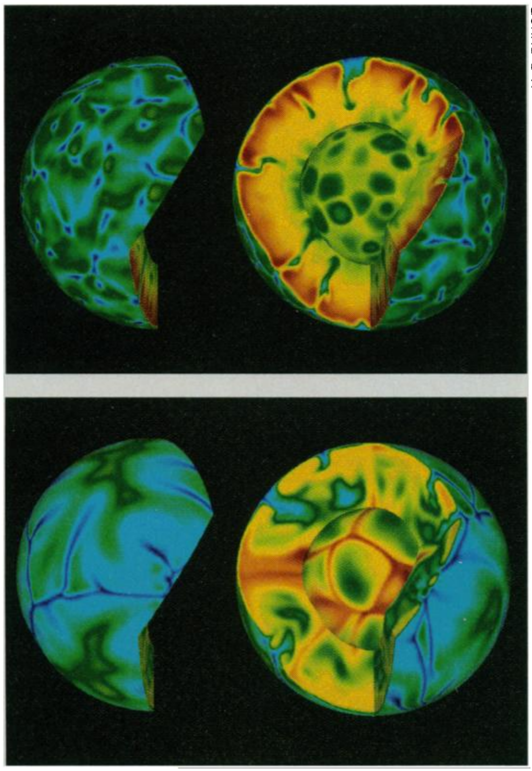
Other geophysicists are delighted with this harmonious finding. It's "a very beautiful paper," says Hans-Peter Bunge of Los Alamos National Laboratory, who thinks it should put an end to dissension about the viscosity numbers. "The study of [gravity] and postglacial rebound can really give you similar answers," agrees Gurnis. And the answers point to a picture of the mantle—O'Connell doesn't want to imply that it has much quantitative significance by calling it a model—with some of the same harmony. The unequivocal viscosity increase with depth means that the lower mantle is a sluggish realm compared to the upper mantle, says O'Connell, but it need not be impenetrable.

An accommodating mantle

In the resulting Earth, says O'Connell, a whole range of features can coexist comfortably, starting with the relative immobility of hot spots, those long-lived centers of volcanic activity such as Hawaii and Iceland. Fed by tall plumes of hot, rising mantle rock, they seem to migrate, but at only about a fifth the rate of tectonic plates. Calculations by Mark Richards of the University of California, Berkeley, and more recently by O'Connell suggest that plumes could not resist the plate-tectonic tide unless they were anchored in a stiff lower mantle. At the same time, Richards has argued that the sharp turn taken by the huge Pacific plate about 43 million years ago could not have been so abrupt if the plate were not sliding on a lower viscosity upper mantle. A mantle that stiffens with depth could neatly explain both kinds of behavior.

A stiffer lower mantle could also explain the huge scale of the areas of rising hot material and cooler sinking material that seismic images of the mantle reveal. In a state-of-the-art computer model of mantle mixing run recently by Bunge and his colleagues, a mantle with a small viscosity gradient produced rising and sinking regions with an unrealistically close spacing. Only a model mantle that is much stiffer toward the bottom develops the global scale structures that the seismic images show.

A stiff lower mantle would satisfy geochemical evidence as well. The proportions of lead isotopes in some volcanic rocks seem to require that the rocks were derived from parts of the mantle that remained isolated from the rest of the planet for 0.5 to 2 billion years, notes geochemist William White of Cornell University. And helium-3, which is a "primordial" isotope that could not have been produced by radioactive decay, appears in such abundance at the Earth's surface that it may still be leaking out of some mantle reservoir that has never mixed with the rest of the mantle for the entire 4.5 billion year age of Earth.



Model behavior. A computer model of a mantle with a constant viscosity has finer scale upwellings and sinking regions *(top)* than the real Earth. A model that stiffens with depth is more realistic *(bottom)*.

To some geochemists, such results have implied a tight seal between the lower mantle and the upper. But in O'Connell's extremely stiff, sluggish lower mantle, that's no longer necessary. He envisions blobs of rock in the lower mantle that are even stiffer than their surroundings because of their different composition and could easily survive for billions of years, according to new computer modeling by Michael Manga of the University of Oregon.

That way, O'Connell can satisfy the geochemistry without ignoring the growing evidence that some traffic between the upper and lower mantle does take place. As improving seismic imaging sharpened the view of descending slabs, it appeared that while some slabs were piling up at the 660-kilometer boundary, others might be sinking hundreds if not thousands of kilometers farther.

Such evidence had already spurred some researchers to seek compromises between layered and whole-mantle mixing. In the 1980s, Geoffrey Davies of the Australian National University and Gurnis argued that a stiff lower mantle might resist but not prevent the passage of slabs through the 660-kilometer boundary and slow their mixing with the lower mantle (*Science*, 24 May 1991, p. 1068). More recently, computer modelers have envisioned another kind of semipermeable boundary, which would hold up descending slabs until enough had accumulated to break through into the lower mantle in a massive "avalanche" of episodic mixing (*Science*, 4 December 1992, p. 1576).

Neither compromise has won the day, however. Davies and Gurnis's picture might not isolate pockets of lower mantle long enough to explain the helium data, according to O'Connell. And mantle avalanches would trigger sudden shifts in Earth's pole of rotation, but magnetic records of ancient pole positions show nothing like that for the past 100 million years or so, notes Bunge.

With Mitrovica's viscosity numbers behind it, O'Connell's picture of Earth's interior may stand a better chance, says mineral physicist Lars Stixrude of the Georgia Institute of Technology, who calls it a "very attractive ... way of reconciling the geochemical and mineral physics evidence and the seismological results."

Then again, says Carl Agee of Harvard, "you're never sure whether it's a unique model or simply an attempt to find a happy medium." To help resolve that question, researchers are sharpening their seismic view of the mantle, especially its still-fuzzy middle parts where the fate of descending slabs is hard to trace, by installing a global network of modern digital seismographs. And back in the lab, computer modelers are closing in on the spatial resolution they need to mix everything they know about the deep Earth—including rocks of just the right stiffness—and see how they flow.

–Richard A. Kerr

Additional Reading

H.-P. Bunge, M. A. Richards, J. R. Baumgardner, "Effect of depth-dependent viscosity on the planform of mantle convection," *Nature* **379**, 436 (1996).

J. X. Mitrovica, "Haskell [1935] Revisited," *J. Geophys. Res.* **101**, 555 (1996).

M. Manga, "Mixing of heterogeneities in the mantle: Effect of viscosity differences," *Geophys. Res. Lett.*, in press.

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