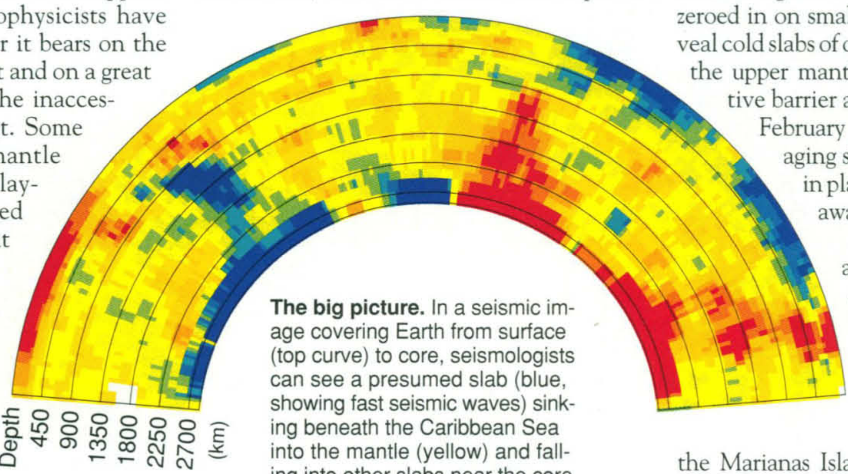
Deep-Sinking Slabs Stir the Mantle

New images of Earth's interior may end a long-running debate by showing that cast-off slabs of surface rock sink to the very outskirts of the core, mixing the mantle from top to bottom

SAN FRANCISCO—Over the eons, pieces of Earth's ocean floor have vanished like the lost island of Atlantis, slowly sinking below the surface in the stately cycle of plate tectonics. But where do these great slabs of oceanic plate go, and what happens to them inside Earth? Geophysicists have long pondered the issue, for it bears on the inner workings of the planet and on a great debate about the mantle, the inaccessible realm below the crust. Some have suggested that the mantle is divided neatly into two layers, with the slabs confined to the shallow top layer. But many seismologists, painting increasingly detailed mantle images with deep-probing seismic waves, have argued with growing confidence that the slabs dive to the very bottom of the 2900-kilometer-deep mantle, stirring it from top to bottom.



S. GRAND/U. TEXAS, AUSTIN

The big picture. In a seismic image covering Earth from surface (top curve) to core, seismologists can see a presumed slab (blue, showing fast seismic waves) sinking beneath the Caribbean Sea into the mantle (yellow) and falling into other slabs near the core.

Now, in the view of many seismologists, two detailed seismic images of Earth's interior clearly show that the burial ground of these "lost slabs" is indeed deep within the bowels of the Earth. The discovery suggests that the lower mantle is an integral part of the engine of plate tectonics, which recycles old, cold slabs and sends hot rock back toward the surface.

The new studies, done by independent teams using different kinds of data, have so impressed geophysicists that the great mantle debate may be over. "There's no doubt—you see the slabs clearly penetrating all the way from the surface to the core-mantle boundary," says seismologist Michael Wysession of Washington University in St. Louis. "In my opinion, this is the final argument. I'm convinced it's some form of whole-mantle circulation." Although some seismologists are less adamant than Wysession, most agree that whole-mantle mixing is the most reasonable interpretation of the new images, presented here at the December meeting of the American Geophysical Union (AGU). "There's now enough evidence to see that, indeed, in some areas, the slabs do penetrate into the lower mantle," says seismologist Barbara Romanowicz of the University of California (UC), Berkeley. "It's hard to see what else it could be."

Two layers or one?

Since the 1960s, geophysicists have known that Earth's internal fires—stoked by heat leaking from the core and by radioactive decay in mantle rock—drive slow convection in the mantle, as a stove burner roils a pot of water. This heat-driven engine reshapes Earth's surface, as tectonic plates move across the surface and then plunge into the interior at so-called subduction zones. But the nature of this convection has long been debated. Laboratory experiments on rocks thought to match the composition of the mantle, plus seismic and other data, suggested that, below a depth of 660 kilometers, the mantle becomes denser and more viscous, like molasses layered beneath water. So, some researchers suggested that each layer churns separately, with no mixing between them.

Some seismologists were slowly putting together a different picture, however. By the early 1980s, they were seeing a glimmer of recognizable slabs in their images of the mantle, assembled from data on the speeds of seismic waves traveling from earthquakes to receivers along many different paths through Earth (*Science*, 17 August 1984, p. 702). A wave's speed depends on the rock's temperature—the hotter the rock, the slower the speed—and composition; as a result, cold, dense slabs speed up the waves passing through them. To form an image of slabs in the mantle, seismologists need the seismic velocity at each spot along a wave's path and so must mathematically combine tens of thousands of paths. A favorite technique is akin to the computerized axial tomography, or CAT, scan that can turn x-rays crisscrossing your head into a three-dimensional image of your brain.

The early mantle scans were pretty blurry, but some by Thomas Jordan of the Massachusetts Institute of Technology (MIT) and Kenneth Creager of the University of Washington zeroed in on small regions and seemed to reveal cold slabs of oceanic plate diving through the upper mantle—and through the putative barrier at 660 kilometers (*Science*, 7 February 1986, p. 548). But later imaging showed that the barrier does in places deflect descending slabs away from the deep mantle.

Arguments and counterarguments flew as each side continued to amass new evidence. In recent years, for example, regional seismic imaging around the Pacific Ocean at places such as the Sea of Okhotsk, the Marianas Islands, and central Java "can most easily be interpreted as slabs going through and penetrating to depths of at least 1000 kilometers," says Thorne Lay of UC Santa Cruz. But just as the barrier to the lower mantle seemed to be smashed, mineral physicists investigating the properties of presumed mantle minerals in the lab began suggesting that the barrier itself is a wide zone, rather than a wall, that stretches down to 1000 kilometers.

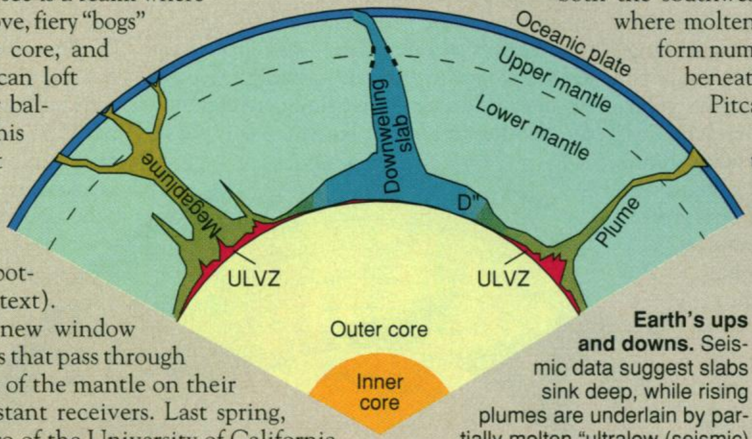
With the presentation of the new global imaging studies at the AGU meeting, that debate has now swung heavily in favor of deep slab penetration and whole-mantle mixing. The two groups, led by Stephen Grand of the University of Texas, Austin, and by Rob van der Hilst of MIT, presented the clearest images yet of the entire mantle. Improvements included several kinds of corrections to the seismic wave paths reported by the International Seismological Center, such as precisely relocating source earthquakes, and the use of shorter wavelength waves that can create sharper pictures. The images show slabs extending at least 1000 kilometers below the 660-kilometer barrier at many places around the Pacific where slabs are subducting into the mantle today. "There is no evidence for a barrier to mantle flow at 1000 kilometers," says van der Hilst.

The slab graveyard

In regions of past subduction, where thousands of kilometers of ocean crust vanished

20,000 Leagues Under the Earth

There's no lack of geological processes to study on Earth's surface, but another place on Earth, or rather inside it, may be almost as dynamic. At last month's fall meeting of the American Geophysical Union (AGU) in San Francisco, seismologists sharpened their view of the lowermost mantle, a shadowy land almost 3000 kilometers down. What they see is a realm where "continents" may fall from above, fiery "bogs" stew above the molten iron core, and whole chunks of landscape can loft upward like so many hot-air balloons. Strange as it seems, this topsy-turvy world is just what you would expect to find at the base of the grand circulation pattern that seems to link our own world with the bottom of the mantle (see main text).



Earth's ups and downs. Seismic data suggest slabs sink deep, while rising plumes are underlain by partially molten "ultralow (seismic) velocity zones," or ULVZs.

E. GARNERO/UCSC

Seismologists owe their new window on this realm to seismic waves that pass through the lowermost 20 kilometers of the mantle on their way from earthquakes to distant receivers. Last spring, seismologists Edward Garnero of the University of California (UC), Santa Cruz, and Donald Helmberger of the California Institute of Technology showed that compressional seismic waves (the analog of sound waves in air) traveling at these depths slow down by about 10% when passing beneath the central Pacific. Slower waves usually mean hotter rock, but such a whopping seismic retardation would require either rock that has partially melted into a stiff mush or a dramatically different rock composition.

At the AGU meeting, mineral physicist Quentin Williams and seismologist Justin Revenaugh of UC Santa Cruz and Garnero reported new evidence that this "ultralow-velocity zone," or ULVZ, consists of partially melted rock. Seismic shear waves, which resemble the undulations of an ocean wave, are particularly sensitive to the stiffness of rock. If the rock in the ULVZ were partially melted, it would slow the shear waves much more than compressional waves. After analyzing waves from 315 earthquakes, the team found that shear waves are indeed slowed three times as much as compressional waves in this region. "The abundance of evidence favors partial melting," concludes Williams.

The Santa Cruz group also reported that they had broadened their search for the ULVZ beyond the southwest Pacific to include 44% of the globe. They found a strong tendency for the ULVZ to be detectable beneath relatively hot portions of the lower mantle identified by other seismic surveys, and undetectable beneath colder regions. The ULVZ also showed up beneath both the southwest Pacific and Africa, areas where molten rock reaches the surface to form numerous volcanic hot spots, and beneath the hot spots of Hawaii, Pitcairn Island, and Iceland.

To the Santa Cruz group, this link between partially molten deepest mantle, hot areas a few hundred kilometers above, and surface hot spots suggests that plumes of hot rock rise to the surface from the deepest parts of the mantle. Hot plumes have been imaged in the upper mantle, but, for over 25 years, geophysicists have debated how deep their roots go. Now, Williams and his colleagues propose that plumes rise from regions of thick ULVZ, which could cause a plume because the rock's relative fluidity could lead to instability and a plume lift-off. Or the cause and effect might be reversed, Williams says, with the plume causing the thick ULVZ by drawing hot rock upward and thickening an existing but undetectably thin ULVZ.

The absence of a thick ULVZ beneath colder mantle also suggests the same mantle circulation pattern that other seismic images imply, Williams says—the descent of cold slabs of tectonic plate from the surface all the way to the lower mantle. Indeed, the colder regions of lowermost mantle coincide with places where the great, cold slabs of tectonic plates have fallen from the surface during the past 200 million years. It all adds up to a picture of the lowermost mantle as a place where sunken slabs are piled to form relatively cold "continents," surrounded not by seas so much as fiery bogs of partially molten rock that can rise into towering plumes toward the surface—our own world in a fun house mirror.

–R.A.K.

long ago into the planet's interior, the slabs have plunged even farther into the lower mantle. Both studies, for example, reveal great slablike features 500 kilometers wide and many thousands of kilometers long hanging in the lower mantle below the now-vanished Tethys Ocean from the central Mediterranean to Indonesia and under the western Americas from Siberia to South America. And in two other places where the images are particularly sharp due to numerous seismic ray paths—beneath the Caribbean and Central Japan—both studies show slablike features that extend from the top to the bottom of the mantle, just above the molten iron core. "It really looks like slabs slide down to [the mantle bottom]," says Grand.

When they get there, he says, they appear to spread out. On the basis of earlier, fuzzier images, some researchers had suggested that the last 300 kilometers of mantle above the core, dubbed the D" layer, is a graveyard of old slabs that have come to rest on the bottom. Data from core-skimming seismic waves, compiled last year by Washington University's Wysession, supported that view. And now the broad pattern of fast and slow seismic velocities in the D" layer of both new images confirms the pattern, says Grand. As glimpsed before, the seismically fast zones of possible sunken slabs appear beneath zones of subduction over the past 150 million years, while the seismically slow, presumably hotter parts of D" fall beneath the southwest Pacific and Africa, where no subduction has occurred in the past 200 million years.

These deep-diving slabs imply a simple mixing pattern for the mantle, says mantle modeler Michael Gurnis of the California Institute of Technology (Caltech). Both studies suggest that mantle downwelling occurs along only a few lines where cold slabs descend, and hot, buoyant mantle—something seismic imaging has trouble rendering in any detail—rises between these descending arms of mantle circulation (see diagram and sidebar). It seems no more complicated than the broad pattern of plate tectonics seen at the surface. Says Gurnis: "It really solves, I think for good, this issue of whole-mantle versus upper mantle convection. There is whole-mantle convection, and [its form] seems to be rather simple."

Don L. Anderson of Caltech, a longtime proponent of a layered mantle, admits that the images are impressive. "The amazing thing to me," he says, "is that their models agree so well even though they use completely different data and [analysis] techniques." Van der Hilst and colleagues used only P waves—pressure waves akin to sound waves in the air—that pass directly through the mantle or the mantle and the core. Grand, on the other hand, used only shear waves—undulations that resemble ocean waves and that can follow many different contorted paths through the mantle, such as repeatedly bouncing off Earth's surface into deeper rock, then bending to the surface again.

Still, Anderson and other researchers who have advocated a layered mantle are holding out for more evidence. "I guess I'm not convinced," says mineral physicist Raymond Jeanloz of UC Berkeley. "To what degree is what is inferred from the patterns in the eye of the beholder? I appreciate that the guys who are doing the hands-on data analysis feel the results just leap out at them, that they really see evidence for slab penetration ... but how you link up these blobs of high velocity and whether you infer they represent slabs going straight through [the 660-kilometer barrier] is not quite so obvious to me as it is to them."

Jeanloz and Anderson would both like to know more about the chemistry and physics of the features behind the seismic images. The images could be compared more closely with computer models that simulate how past subduction should have shaped the mantle, Jeanloz suggests. And Anderson would like more comparisons of the seismic data with experimentally determined mineral properties, to prove that the seismically fast features are actually slabs: "Just because you found some [fast] regions, it doesn't mean anything until you know what that means in terms of temperature and chemistry."

To many seismologists, as Gurnis puts it, these are "details" that "remain to be worked out," not fatal flaws. And before such studies are finished, even more persuasive images may appear. Grand notes that there are plenty of seismic data in hand that can be analyzed to sharpen the still-fuzzy spots in the images, which reflect gaps in the distribution of earthquakes and seismic stations. Of course, many mysteries remain, such as whether slabs now imaged only into the midmantle can be seen to extend to the bottom and the ultimate fate of slabs that have come to rest at the core-mantle boundary. Slabs may be buried deep, but that doesn't mean that their rest is undisturbed.

–Richard A. Kerr

AIDS

Advances Painted in Shades Of Gray at a D.C. Conference

Success often comes at a price. Researchers who gathered here last week for the most influential AIDS meeting in the United States heard one speaker after another praise the dramatic advances in drug treatments that recently have captured the media spotlight. But the 2300 attendees also heard scores of reports about the less glamorous task of filling out and qualifying last year's bold claims. "We're not hearing the headline stuff we heard last year. The data at this meeting were much broader and deeper," said the conference's chair, virologist Douglas Richman of the University of California, San Diego (UCSD). Organizers of the 4th Conference on Retroviruses and Opportunistic Infections* also had to contend with their own success: The gathering has become so popular that they had to set strict attendance limits, angering many AIDS activists and scientists who were locked out.

"We must dutifully avoid unwarranted triumphalism [as well as] the undue pessimism that prevails in some circles."

—David Ho

David Ho, head of the Aaron Diamond AIDS Research Center in New York City, set the tone for the meeting in the opening session, when he cautioned his colleagues to put the recent progress in AIDS treatment in its proper perspective. "We must dutifully avoid unwarranted triumphalism [as well as] the undue pessimism that prevails in some circles," he said. "The state of HIV treatment is neither black nor white. We must paint the situation in the proper shade of gray." Indeed, many fundamental questions about the new anti-HIV drugs are still unresolved, including how best to use them and how to assess their limitations. And the treatment picture will take on even subtler shading as drug companies attempt to bring a flood of new drugs to market.

One aspect of AIDS research in 1997 can be rendered in black and white: For the first time since the start of the epidemic, HIV-infected patients and clinicians have at their disposal an arsenal of potent, virus-crippling drugs. A new class of drugs that inhibit HIV's protease enzyme, which the virus uses to assemble new copies of itself, is the arsenal's mainstay. When combined with older drugs like AZT and 3TC that disable the enzyme that copies the virus into the host cell, the protease inhibitors can pound the virus so hard that, in many patients, even the most sensitive tests cannot find it in the blood cells.

Several studies presented at the meeting attempted to assess the impact of the new drug regimens on patients by looking at how frequently they were becoming ill. As AIDS researchers constantly point out these days, reducing the viral load (the total amount of HIV) in a patient's blood does not necessarily mean he or she will suffer fewer AIDS-related diseases. The hope, of course, is that the drugs will help HIV-infected people to live longer. But at present, most drugs win regulatory approval based primarily on viral-load data, and few of the trials measure clinical outcomes.

The largest analysis of links between new drugs and illness was presented by Yves Mouton of Dron Hospital in Tourcoing, France. Mouton and colleagues looked at 7757 patients from 10 AIDS centers in France. In the study period, between the fall of 1995 and 1996, the use of anti-HIV drugs in these patients jumped by 49%. At the same time, AIDS-defining diseases dropped 36%, said Mouton. The number of days patients were hospitalized also plummeted by more than one-third. Mouton attributed these improvements largely to the drugs.

Mary Ann Chiasson, assistant commissioner of the New York City Department of Health, reported similarly upbeat statistics. In New York City, which accounts for 16% of U.S. AIDS cases, AIDS deaths last year dropped by 30%. But health officials did not attribute the drop to increased use of protease inhibitors. According to Chiasson, the AIDS death rate began to fall before the two most powerful drugs reached the market last spring. She suggested that the decline in deaths may instead be linked more closely to an increase in federal funding in 1994 for AIDS patients, which led to better prevention and treatment of opportunistic infections.

* 4th Conference on Retroviruses and Opportunistic Infections, 22–26 January, Washington, D.C.