Plunging Plates Cause a Stir

Scientists are beginning to rally around a decade-old idea that oceanic plates descend into the lower mantle of the earth. These deeply plunging plates are rekindling an even older debate over the flow patterns of the mantle.

By STEFI WEISBURD

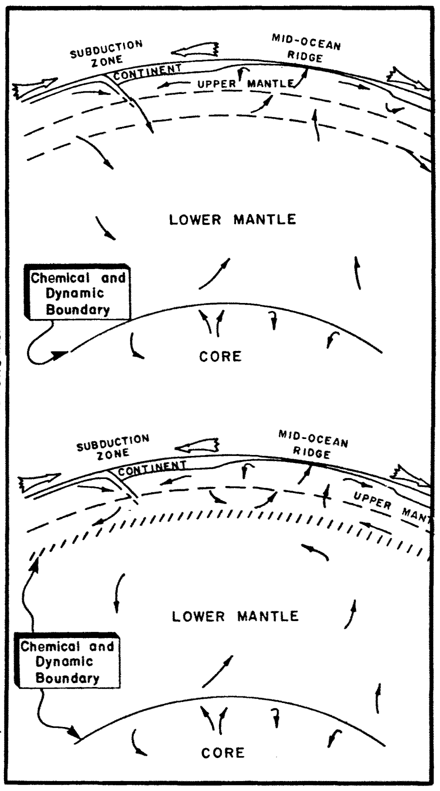
From towering mountain chains to the vast blue depths of the oceans, the face of the earth is geologically varied and forever changing. With the advent of plate tectonics theory in the 1960s, scientists recognized that the earth's surface is continually sculpted by the collisions and movements of the dozen or so plates of the planet's outer shell.

But the plates are only the thin veneer of the planet. If scientists are to understand the forces that drive plate motion and ultimately control the surface topography, they must look much deeper into the earth. They must extend plate tectonics into a third dimension and come to understand the earth's mantle.

Geophysicists in the last decade have come a long way in studying the mantle, especially in their use of seismic waves generated by earthquakes to probe the inner earth. Now, with a variety of techniques, some scientists are making discoveries that challenge traditional thinking about the mantle. In particular, they are finding that oceanic plates plunge deeply into the mantle, crossing what many have viewed as an impenetrable boundary zone between the lower and upper mantle layers.

In this way the findings are bringing some refreshingly new data to a longstanding debate over the flow patterns of mantle rocks. These patterns do more than determine the motion of plates at the surface. Because the mantle accounts for 83 percent of the earth, mantle flow is key to understanding how the earth has cooled and chemically evolved during its 4.5-billion-year history.

For many years, a prevailing view on mantle flow has been that the upper and lower mantle are physically and perhaps chemically different from one another, so that the circulation, or convection, of mantle rocks in one layer is independent and distinct from that of the other layer — just as the movement of heated water has little effect on the motion of an overlying layer of oil. One line of evidence supporting this "double-layer convection" model is that the speed at which seismic waves travel in the mantle changes abruptly at a depth of about 650 kilometers — the boundary line between the upper and lower mantle. Since a wave's seismic velocity depends on the properties of the inner earth, scientists think some fundamental change takes place in the mantle rocks at 650 km. Researchers agree that a large part of this change is a phase change — a rearrangement of atoms in the mantle rocks caused by increasing pressure. But, because of the sharpness of the 650-km discontinuity, some have also argued that the boundary reflects a change in the mantle composition as well.



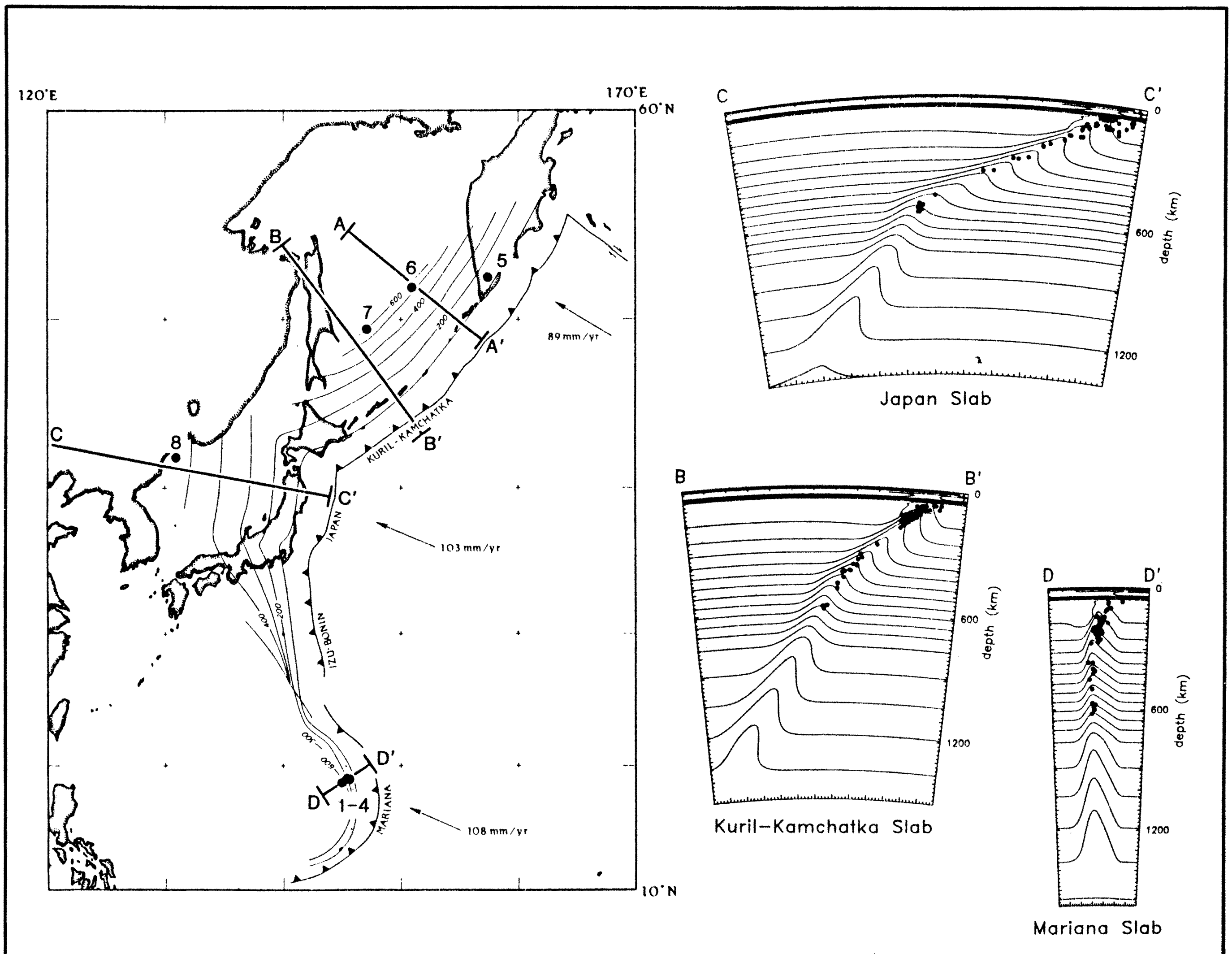
High pressures ensure that the mantle is composed almost entirely of solid rocks, but extreme temperatures cause the rocks to move much like a fluid. The flow rate does not appear very rapid in human terms; rocks move about as fast as fingernails grow. But on the geologic time scales of millions of years, this movement appears much more vigorous. For decades, scientists have debated two models for mantle flow: two-layer convection (bottom), in which upper mantle flow is independent of that in the lower mantle, and whole-mantle convection (top), in which material circulates between the upper and lower layers.

The double-layer convection model has also been bolstered by observations of the deepest earthquakes, which occur in oceanic plates that are subducting, or plunging beneath other plates. Seismologists have found that there are no quakes deeper than about 680 km and that the pattern of faulting in the deepest quakes suggests that the slabs are running into something hard and beginning to break up. This has led many scientists to conclude that subducting slabs do not penetrate into the lower mantle. And if slabs can't penetrate the lower mantle, then it's doubtful that other rocks in the upper mantle move into the lower mantle either.

But geophysicist Thomas H. Jordan at Massachusetts Institute of Technology and others are changing all that. In the mid-1970s Jordan began a series of seismic studies of subduction zones in the Pacific Ocean, all of which have shown that descending plates go deeper than 650 km. Jordan and his students have been analyzing the time it takes for seismic waves from earthquakes in the slab to travel to detection stations.

Seismic waves speed up when they pass through cold material, and since subducting slabs are 500°C to 1,000°C colder than the surrounding mantle, any wave that has traveled through the slab should arrive at a seismic station much sooner than it would if it took the same path through the hotter mantle. Jordan's group has found that waves traveling down and away from deep earthquakes at several subduction zones studied do indeed speed up.

"At each zone we think we can resolve slab penetration to depths exceeding 1,000 km total, or 350 km below the 650-km discontinuity," says Jordan. "And at Kuril [near Siberia] we think we can see the slab down to 1,200 km."



Creager and Jordan/JGR

Jordan and his student Kenneth C. Creager have studied the speeds of seismic waves generated by deep earthquakes (shown as dots in the cross sections above and on the cover) at a number of subduction zones in the western Pacific. Seismic waves passing through the cold descending plates travel faster than waves that move through the hot mantle. As a result, the descending slabs are delineated in the cross sections by contour lines of constant seismic velocity (each line represents a 0.25 kilometer/second increase in velocity from the line above). The plates plunge well below the 650-km boundary between the upper and lower mantle. Jordan does not yet know why there is a bend or kink in some of the subducting slabs around 600 km or so.

"The evidence is getting pretty overwhelming," says geophysicist Paul G. Silver at the Department of Terrestrial Magnetism at the Carnegie Institution in Washington, D.C. "People are coming around to the idea that slabs do penetrate into the lower mantle."

Silver and W. Winston Chan at Teledyne-Geotech in Alexandria, Va., have begun to use other seismic techniques to further test the slab penetration idea. They have noticed that the seismic signals from subduction quakes are complex and rattle on for an unusually long time. The researchers think this is because the detection station, in addition to picking up waves that travel directly from the slab, registers seismic waves that have been bent and deflected toward the station by the slab – just as a lens bends the path of light rays.

Like the scientists studying the travel times of deep earthquake waves, Silver and Chan are concluding that slabs penetrate into the lower mantle. But with their technique, these researchers are finding that the slab structure is more complicated than the simple, smooth sheet envisioned by Jordan and others. In order to explain their data, Silver's group has to assume that there are undulations in the slab or that there is a layer on top of the slab through which seismic waves travel at great speed.

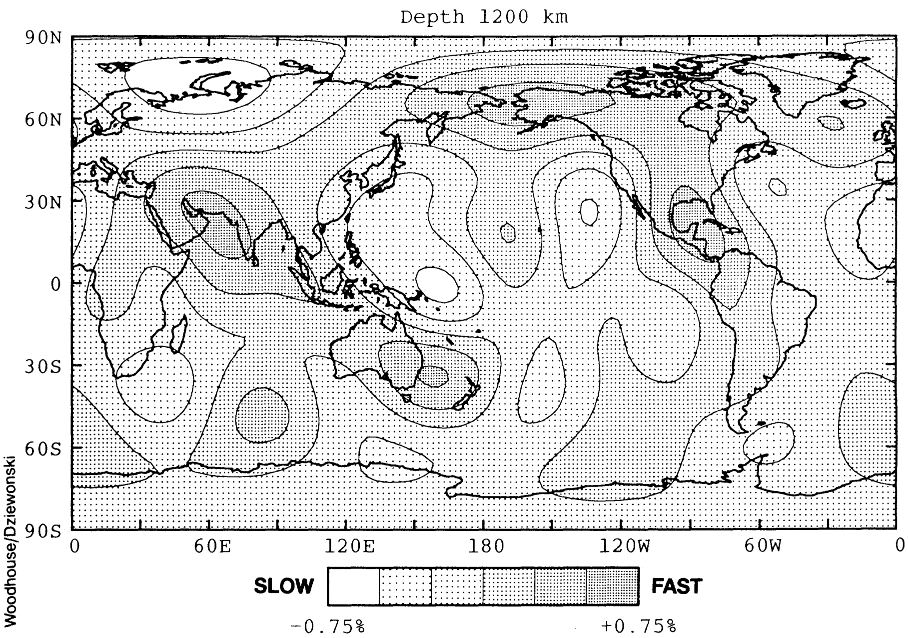
Support for slab penetration comes also from geophysicist Bradford Hager at Caltech in Pasadena, Calif. Hager has been making models of mantle convection to explain the seismicity, orientation of stresses and gravity measurements around subduction zones. He says his models work best if slabs extend into the lower mantle. But because his models also require the mantle viscosity to increase substantially below about 670 km, he thinks slabs slow down as they hit the more viscous lower mantle region.

"I'm halfway between the two camps in that I do think some material does move from the upper mantle into the lower mantle," he says, "but there is also a real qualitative difference in the convective styles between the upper and lower mantles."

Like Hager, John H. Woodhouse and Domenico Giardini at Harvard University have concluded, based on studies of the orientation of deep earthquake faults and slab deformation, that if slabs do penetrate into the lower mantle they encounter considerable resistance. In the Tonga subduction zone near Australia and at a few other sites, they have found that the descending slab thickens and starts to turn in a horizontal direction at about 670 km. Not all zones behave this way, but "at least some slabs don't like to be pushed through this boundary," Woodhouse says. Still, when all the data are taken together, Woodhouse finds the seismic evidence for slab penetration to be very persuasive, although not yet totally conclusive.

In addressing the question of slab penetration and in deciphering the flow patterns of the mantle, Woodhouse and others hold their highest hopes for seismic tomography. This technique, like the computerized axial tomography, or CAT scans, used in medicine, produces three-dimensional maps of the mantle (SN:4/30/83,p.280). Recent tomographic maps by Woodhouse and Harvard colleague Adam M. Dziewonski, as well as by Stephen P. Grand at Caltech, are particularly tantalizing because they reveal a large stripe in the lower mantle through which seismic waves travel very quickly. The stripe extends from a point near Siberia through the Aleutian Islands in Alaska and on to the Caribbean.

"It's not possible to say what this feature is, but it's conceivable that it's some remnant of subduction," says Woodhouse, who adds that the seismic velocities are so great that if the stripe is related to descending slabs it probably represents a large accumulation of slab material and not just the traces of ongoing subduction. Both this stripe and another, extending from the Red Sea to new Zealand, skirt major subduction zones of the present and the geologically recent past. Grand notes, for example, that there is a region of high seismic velocity at about 1,500 km depth under North America, where scientists think a subduction zone existed 100 million years ago; reflecting the westward movement of this zone is another high-velocity area at a shallower depth and more to the west. If the stripes are not slabs that have physically descended into the lower mantle, says Grand, they could be regions in the lower mantle that have been cooled by material in the upper mantle.



Woodhouse/Dziewonski

One intriguing finding that may support the slab penetration idea is that of positive seismic velocity anomalies – regions in which seismic waves travel faster than in surrounding areas – in the lower mantle. These positive anomalies are shown as dark regions in this seismic tomographic map of the mantle at 1,200 kilometers depth. One possible explanation for the fast anomalies is descending plates, which are colder, and hence seismically faster, than the surrounding mantle. The two major anomalies in the map – one extending from Siberia past Alaska and down to the Caribbean, and the other extending from the Red Sea to New Zealand – underlie past and present subduction zones.

In spite of the blossoming interest in slab penetration, the idea is not without its critics. Don L. Anderson at Caltech, in particular, has argued on the basis of laboratory experiments that the mineralogy of the descending plate may exaggerate the seismic speeds of waves traveling in the slab. Because the slab is colder than the surrounding mantle, he says, minerals in the slab go through phase changes different from those of the mantle minerals.

"So instead of the slab just being colder and therefore denser and seismically faster, we have a new suite of minerals that are intrinsically much denser and faster than the normal mantle," he adds. Moreover, Anderson thinks these minerals are anisotropic, or aligned in the direction of stresses in the slab, so that seismic waves traveling along the slab propagate even faster. The end result, he says, is that what seismologists have intepreted as a long, seismically slow slab may really be a short, seismically fast slab. "By considering these mineralogical arguments, you can account for the whole anomaly with just 50 km or so below the deep earthquake," he concludes.

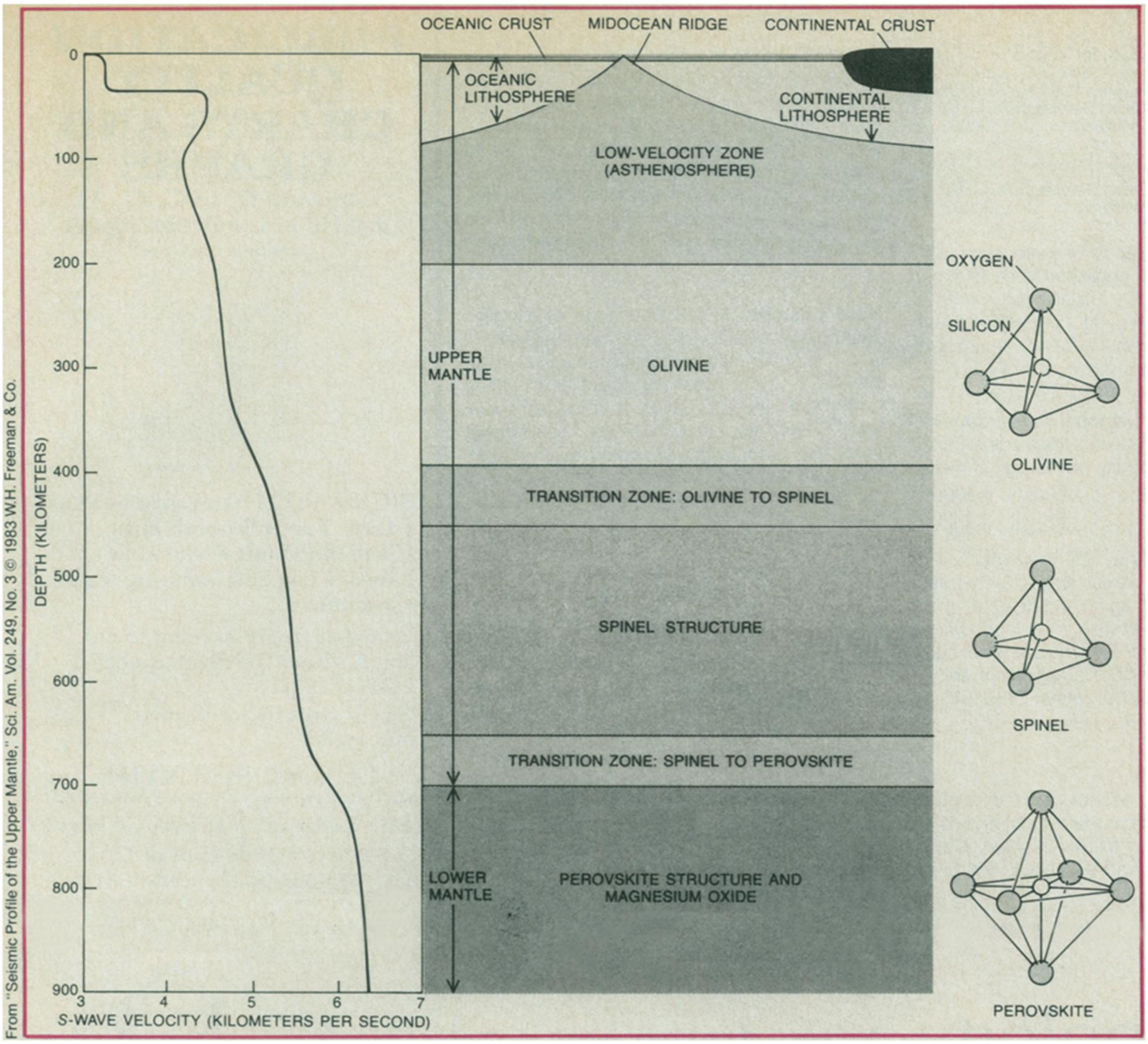
Jordan, who did his doctoral thesis under Anderson, says his group has found no evidence for anistropy. Even if the seismic velocity in the slab were as great as Anderson proposes, "you'd still have to have significant slab penetration below 650 km," Jordan argues. "We have something that looks like a slab, smells like slab—all right below [where we know there is] a slab."

If Jordan's interpretation is correct, then slabs are clearly showing that there is mixing of material between the lower and upper mantle. Assuming that all oceanic plates eventually get shoved into the lower mantle, Jordan calculates that the entire volume of the upper mantle would be thrust into the lower mantle about every billion years, or at least four times during the earth's past history. This implies that the upper and lower mantle should be fairly well mixed together.

Geochemists, however, do not take well to the idea of much mixing. Isotopic studies of volcanic rocks suggest that there are distinctly unmixed reservoirs of different rocks in the mantle: regions made up of primitive materials very similar to the composition of the early earth, and regions that have been depleted of certain minerals as material has risen to the surface to form continents and oceanic crust.

Scientists have come up with a spectrum of mantle models having such reservoirs. The strict two-layer model includes a primitive lower mantle and a depleted upper mantle that is very occasionally pierced by rising plumes of primitive material, which eventually form hotspots like the Hawaiian Islands. At the other extreme, some scientists have suggested the "plum-pudding" model, in which reservoirs of different compositions and sizes are laced throughout the mantle. Models like the plum-pudding concept have the best chance at keeping some reservoirs unmixed and isolated while there is mantle-wide convection mixing and remixing other reservoirs. But no modeler has yet devised a convection scheme that satisfies everyone.

Even if modelers were to find a way to reconcile the isotopic and seismic studies, they would still have to grapple with the geochemical studies of the average properties of the mantle, conducted by Raymond Jeanloz at the University of California at Berkeley. He and his co-workers have subjected upper-mantle minerals to the pressures and temperatures existing in the lower mantle. The resultant density is a few percent less than what seismologists infer for the lower mantle. According to Jeanloz, this means that the chemical composition of



The most direct information about the mantle has come from seismologists who probe the inner earth with waves generated by earthquakes. The speed at which these waves travel depends on the properties of mantle rocks. One of the largest changes in seismic speed occurs at about 650 kilometers depth. This change is brought about, at least in part, by a phase transformation: The atoms in the mantle minerals are rearranged by the high pressures into a denser and seismically faster structure.

the lower mantle is slightly different from that of the upper mantle.

"That's a small effect, but unfortunately it has a big consequence," he muses. "If the lower and upper mantle really are different in composition, then it's very hard to accept that they've been stirred around over geological time periods, because by now you'd expect them to be all intermixed."

The idea of an intimately connected upper and lower mantle challenges not only geochemists but also scientists who study how the earth has cooled since its hot inception. Heat escaping from the radioactive core is what ultimately powers the motions of the plates at the surface. The intermediary between the core and the surface is the mantle: Heat passes through the mantle by the relatively slow conductive process and by the more efficient convection process, in which hot mantle material moves toward the surface. If the mantle were divided into two separately convecting layers, the passage of heat from the lower to the upper mantle would be limited primarily to conduction. This would keep more heat inside the earth and might explain why the earth is still so tectonically active long after many of its planetary neighbors have run out of steam.

The discrepancies between the slab observations and the geochemical and heat considerations might be resolved, says Jeanloz, if future studies were to show that there is only a limited amount of intermixing. "Maybe every once in a while something in the lower mantle gets very hot and burps up into the upper mantle," he says. The question then becomes: How common is slab penetration? Does *every* subducting plate *always* punch through to the lower mantle?

"We're now on the hairy edge of what any of us can resolve and really convince our colleagues of," says Jeanloz. In the coming years, both seismic studies and laboratory experiments — particularly those dealing with the composition and structure of minerals at the magical 650-km boundary — should help guide scientists through the paradox.

For Jordan, all of these discussions, even the talk critical of slab penetration, is music to his ears. After writing papers on slabs for 12 years, he says, "the exciting thing is that people are now focused on this as an issue." And according to a number of observers, slab penetration is the hottest topic in geophysics today.

"A lot of people believe that we're in a crisis in the geosciences right now," says Jordan, "because the earth has gotten so complicated that we can't say anything about it anymore" — for every argument about the way the planet works, there is a counterargument. And many scientists have cited the long debate on layered versus whole-mantle convection as a prime example of this scientific quagmire, he says. Jordan believes that until now there hasn't been any strong evidence to break the deadlock, because most of the data used have been very indirect.

"If the observations [of slab penetration] are correct — and I don't see any reason why they would be substantially incorrect — we are [directly] observing deep mantle circulation," he says. "The mantle might be stratified at depths greater than 650 km, but I would say that the [strictly two-layer convection] model is knocked in the nose by these observations." □