Sinking Slabs Puncture Layered Mantle Model

Seismologists are finding that oceanic plates sinking into the mantle plunge right through the supposedly impenetrable boundary between the upper and lower mantle

Most of Earth is mantle rock sandwiched between a thin veneer of crustal rocks and the liquid core. Geophysicists and geochemists can never get their hands on the mantle, but that has not stopped them from trying to guess what it is like and how it shapes the visible Earth. Now it appears that the deepest part of the mantle may have a closer link to the surface than once thought.

The mantle is an odd place to figure out. Mantle temperatures and pressures are so high that solid rock slowly flows, but despite this mobility some researchers have argued that the upper and lower portions of the mantle are in fact like oil floating on water and never the twain shall mix. Neither the commotion in the upper mantle caused by the operation of plate tectonics, nor the flow of heat away from Earth's interior, would break down the boundary between the upper and lower mantle, according to this thinking. But many seismologists believe that they now have found rock from the upper mantle, from which the continents have supposedly been made, as well as rock from the crust sinking into the lower mantle, where rock unchanged since the early days of Earth was thought to be isolated.

The seismological evidence bearing on the existence of a layered mantle has done an abrupt about-face of late. The most frequently cited seismological evidence has been the absence of earthquakes below a depth of about 650 kilometers, the putative boundary between upper and lower mantle. Earthquakes typically fracture the 125-kilometer-thick oceanic plates as they sink, that is, subduct, into the upper mantle, but the earthquakes always disappear before the descending slabs pass through the sharp 8 percent jump in density marking the boundary at 650 kilometers. The cessation of earthquakes right where slabs encounter the obstacle of a density increase suggested to many that the slabs as well as the earthquakes stop at 650 kilometers. Slabs go no deeper than their earthquakes, it was assumed.

Robert Engdahl of the U.S. Geological Survey in Denver and David Gubbins of the University of Cambridge have recently shown that slabs of oceanic plate do extend deeper into the mantle than their accompanying earthquakes. They studied how fast seismic waves traveled away from earthquakes in the central Aleutian subduction zone depending on the direction the waves took. Seismic waves speed up 4 to 11 percent while traveling through descending slabs, which are 700°C colder and thus denser than the surrounding mantle. Engdahl and Gubbins found that waves passing downward below the slab's deepest earthquakes at 250 to 275 kilometers still sped up; the central Aleutian slab must extend below its deepest earthquakes, they inferred. "You can't escape that conclusion," says Engdahl, and that slab may extend as deep as 400 kilometers. Perhaps the earthquakes fail to extend as deep as that, says Engdahl, because at this particular site the slab might become too hot to remain brittle enough to fracture in an earthquake.

Deep penetration of slabs shows that the lower mantle has not entirely escaped mixing with material of crustal and upper mantle composition.

Thomas Jordan of the Massachusetts Institute of Technology has argued for 10 years that similar studies of seismic wave travel times reveal the extension of seismically quiet slabs below the supposed barrier at 650 kilometers. Most seismologists finally believe that he, along with his student Kenneth Creager, have made the point. Recently, Jordan, Creager, and another student, Karen Fischer, have presented travel-time evidence of slab penetration to at least 1000 kilometers at five sites around the western Pacific—the Tonga, Mariana, Izu-Bonin, Japan, and Kuril-Kamchatka subduction zones. At each of the five, the slab appeared to extend to at least 1000 or even 1200 kilometers, but the method cannot detect penetrations beyond 1200 kilometers, if they exist.

At the American Geophysical Union (AGU) meeting last December, where the MIT group presented these results, the only fundamental reservation raised came from Don Anderson of the California Institute of Technology. In informal but extended remarks, he argued, on the basis of laboratory and theoretical studies, that under mantle temperatures and pressures mineral crystals within the slab would align themselves so that not only temperature but also the orientation of the crystals with respect to the path of the seismic waves would influence travel times. That, he said, would greatly exaggerate penetration depths.

The responses were not particularly supportive of Anderson's objection. Norman Sleep of Stanford University questioned whether Anderson's proposed mineral orientation, called anisotropy, would be as pervasive and as uniform as seemed necessary to produce a significant effect. Jordan countered that even if it was, "In no way can this explain what we've seen. We've looked for such effects and thus far have seen no evidence of it." Regardless of anisotropy's effects on velocities within the slabs, he said, the observations require penetrations of more than 100 kilometers beyond the 650-kilometer boundary. No variations in travel time with varying direction remain unexplained, and two different types of seismic waves, compressional and shear waves, bear the same relationship in their studies of slabs as is found elsewhere in the mantle.

The other objection to deep penetration that is sometimes raised is the boundary's apparent deflection of the Tonga slab. Domenico Giardini and John Woodhouse of Harvard University have studied how earthquakes fracture and deform the Tonga slab. The slab shortens and thickens as it descends, and as it approaches the boundary, there located at about 670 kilometers, the slab bends to the side, as if encountering an impenetrable barrier. But Woodhouse does not see this as automatically excluding slab penetration. He concludes that the slab either does not penetrate the barrier or only does so with great difficulty after being considerably deformed. At the same time, he finds Jordan's work fairly convincing. It seems likely that slabs do punch through what must be considerable resistance at the boundary, he says, but he finds it difficult to reconcile the deformation that he sees in the Tonga slab with the apparent lack of deformation that Jordan seems to see.

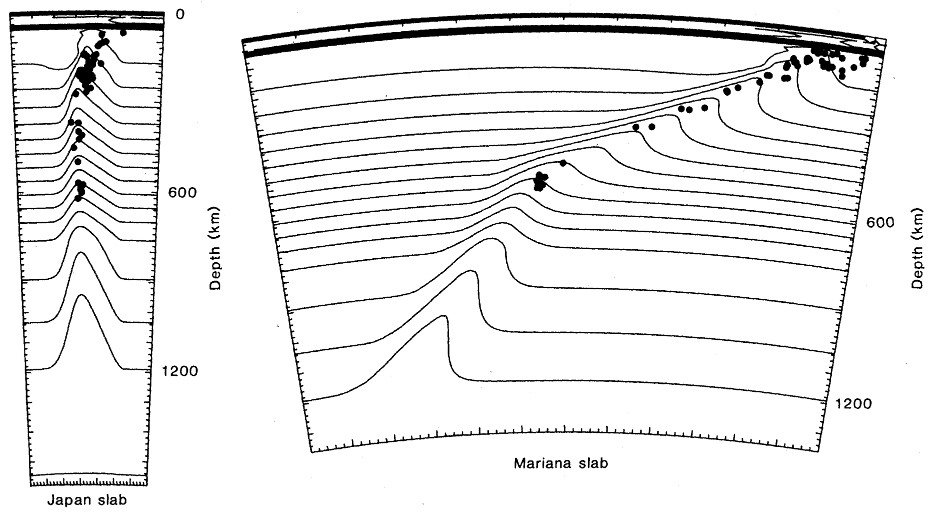
Jordan responds that Tonga is a special site, where a slab is more likely to deform, and that in any case his technique is not particulary sensitive to deformation. Although the slab in the central Tonga trench does appear to penetrate deeply, the central region is the simplest geometrically. Outside of it, there are complications evident even in Jordan's data that could signify significant deformation, he says. In addition, as noted by Giardini and Woodhouse, Tonga is the only subduction zone studied that is being dragged sideways by plate motion, a complication that might explain the observed deformation.

New support for deep slab penetration appeared at the AGU meeting in the form of another seismic probe of cold slabs that is independent of the travel time technique. Paul Silver and Winston Chan of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington reported that whatever it is beneath the deepest earthquakes that speeds up seismic waves also deflects some waves and even splits others. The only explanation that Silver and Chan can find is that subducting slabs penetrate at least 300 to 400 kilometers into the lower mantle.

The Carnegie group looked at three different kinds of shear waves, each following a different kind of path through the mantle, in order to rule out possible extraneous effects due to properties of the earthquakes themselves or of other parts of the mantle. To maximize any effects of the slab, they looked through the length of the Kuril-Kamchatka slab by examining waves received in North America, which lies in line with that slab. What they saw from North America was the apparent deflection of waves by the cold, high-speed slab away from the line of sight. These waves are broadened and appear split into multiples of their original form.

When Silver and Chan examined seismic waves from the Izu-Bonin and Japan slabs, which point toward Europe instead of North America, they found no shadowing, broadening, or increased wave complexity. The only way that they could produce the observed effects in mathematical models of wave behavior was to extend the Kuril-Kamchatka slab to at least 1000 kilometers and to curve the deep slab downward, just as Creager and Jordan did to explain their travel time data.

The discovery of subducting slabs penetrating into the lower mantle will help geophysicists draw new pictures of how the earth transforms particular regions of its mantle into magma of a new composition and carries it to the surface to form continents and ocean basins. A much discussed mantle model keeps the upper and lower mantle totally separate while doing this. Heat from Earth's interior churns the lower mantle by driving convection there and the heat conducts across the boundary toward the surface, but rock does not mix across the boundary. Only the occasional plume of hot mantle rock breaks through to form a hotspot, such as the Hawaiian volcanoes. In this layered model, continental and oceanic crust are derived solely from the upper mantle, altering its composition in the process.



Two slabs descending into the lower mantle

By gauging the speed of seismic waves from earthquakes (dots), Thomas Jordan, Kenneth Creager, and their colleagues at MIT have shown that ocean plates sinking into the mantle pass through the boundary at a depth of about 650 kilometers between the upper and lower mantle. The gently inclined Japan slab and others do dip downward just before passing through the boundary. The Japan slab extends as far as southern China. The slabs are visualized here by contours of seismic wave velocity, which is higher in the cold slabs.

Geochemists have tended lately to complicate this two-layer model by claiming that rocks found at the surface must have come from at least three if not many more mantle reservoirs that have remained intact for more than a billion years. Attempts to arrange enough source reservoirs so that they are not torn apart by convection but can still send material to the crust has produced a plethora of models, enough, as one researcher observed, to have the number of models approach the number of workers in the field. The ultimate model of whole-mantle convection, in which the 650-kilometer boundary plays little or no role, is called the plum pudding model—mantle blobs of all sizes having differing composition are strewn throughout a mantle that is being stirred from top to bottom.

At a minimum, deep penetration of slabs shows that the lower mantle has not entirely escaped mixing with material of crustal and upper mantle composition. Strict two-layer models appear to be untenable if seismological observations are to be believed. That complicates the task of keeping intact reservoirs that appear to contain rock little altered since Earth's formation. On the other hand, ocean crust in the lower mantle might make a good source for magmas that form certain ocean islands.

Lower mantle slabs do not necessarily prevent the 650-kilometer boundary from playing a role in mantle dynamics. Subducting slabs have the strongest density contrast of any part of the mantle, so the boundary might well give way to them while being sturdy enough to contain smaller, less powerful disturbances. Even so, if all oceanic plates are sinking into the lower mantle, a volume of rock equal to that of the entire upper mantle would be thrust into the lower mantle every billion years, so some return flow to the upper mantle might occur at an as yet unknown location. A fairly direct test of any model would be the determination of the nature of the boundary. Does the change in density over a few kilometers result from a change of composition, a pressure-induced change in mineralogy, or both? Laboratory studies of minerals under mantle conditions may provide the answer. ■

RICHARD A. KERR

ADDITIONAL READING

E. R. Engdahl and D. Gubbins, "Simultaneous travel-time inversion for earthquake location and subduction zone structure," *Eos* **66**, 1086 (1985).

K. C. Creager and T. H. Jordan, "Slab penetration into the lower mantle beneath the Mariana and other island arcs of the northwest Pacific," *J. Geophys. Res.*, in press.

D. Giardini and J. H. Woodhouse, "Deep seismicity and modes of deformation in Tonga subduction zone," *Nature (London)* 307, 505 (1984).

P. Silver and W. Chan, "Subducted slabs in the lower mantle: evidence from body wave multipathing," *Eos* **66**, 957 (1985).