A Generational Rift in Geophysics

An eminent geophysicist and his intellectual offspring are locked in a decades-long debate on a central question of geophysics: the behavior of Earth's deep interior

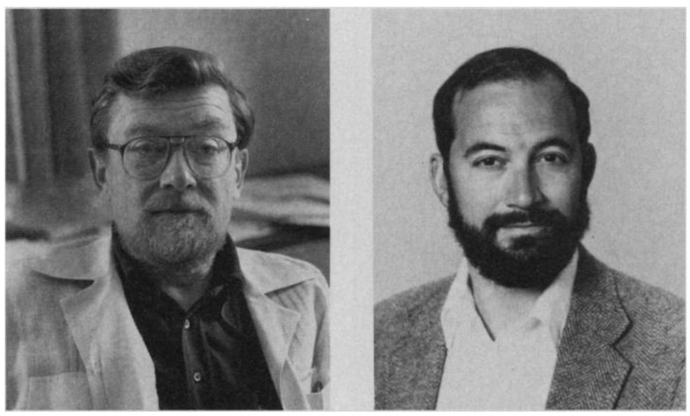
FROM THEIR RÉSUMÉS, geophysicists Don L. Anderson, 57, and Thomas H. Jordan, 41, would seem to be made of much the same stuff. Both received their advanced degrees from Caltech—Jordan 18 years ago as Anderson's student. Both have received similar honors from their colleagues. And professionally, both want to know how the insides of Earth work, how the heat escaping from the planet's inner fires drives volcanoes and earthquakes and builds mountains.

And by all reports the father-son relationship was an amiable and productive one. "He was my mentor," says Jordan of Anderson, who for 22 years has headed Caltech's Seismological Laboratory. "A lot of the way I am as a scientist is because of the way he is. His interests are extremely broad and wide-ranging."

So why can't these two intellectual blood relatives agree on anything? Within a couple of years of Jordan's departure in 1972 from Caltech, the up and coming young scientist and the senior researcher were at academic loggerheads. Their continuing debate, as much as anything else, has defined the opposite extremes of what has become a central issue in geophysics: how does Earth carry the heat of its molten core and overlying mantle to the surface? Does the mantle roil from top to bottom, like water boiling in a pot on a stove, much as Jordan proposes? Or, is there a physical barrier in the upper part of the mantle across which no material can pass, as Anderson would have it?

The outcome of the debate has considerable ramifications for geology. If Anderson's stratified model of the mantle is correct, no material of the deep interior, only heat, would pass from the lower mantle to the upper mantle, leaving the lower mantle sealed away for all time. In that event, the upper mantle would have to be the source of all crustal rocks, including volcanic hot spots such as the island of Hawaii, as well as the ultimate dumping ground for old ocean tectonic plates. But if Jordan's model of a more or less mixed mantle proves correct, his adviser's world view will crumble.

Since their first intellectual divergence, neither mentor nor ex-protégé has turned back. "They each developed a vision of the earth and then went after evidence to support that vision," says Jean-Bernard Minster of Scripps Institution of Oceanography, who was a fellow student of Jordan's at Caltech. "These are two outstanding and extremely competitive geophysicists," he says.



Like father, like son? *Since Thomas Jordan (right) was Don Anderson's student, they have had their differences about how Earth works.*

Their different philosophical approaches to ferreting out the secrets of the deep Earth may also have contributed to their disagreements. Where Jordan sees a sharp picture of the interior in seismic data, for example, Anderson will see confusion and unaccounted for complexity until more constraints from lab and theory are brought to bear.

The resulting confrontations have at times been pointed, but Anderson and Jordan have always maintained academic decorum. At their talks at meetings of the American Geophysical Union (which Anderson currently heads), some people might look for blood to be spilt, notes Minster, but Anderson and Jordan "are too civilized for that."

No one has won this bloodless battle yet, but to most observers the struggle seems worthwhile. "I think it's quite constructive," says Bradford Hager, who recently left Caltech for the Massachusetts Institute of Technology, where Jordan is now head of the Earth, Atmospheric, and Planetary Sciences Department. "One of Don Anderson's major contributions has been forcing people to question their assumptions" and thus strengthening the science all around.

Assumptions have inevitably played a crucial role in the study of the deep Earth. Twenty-nine hundred kilometers thick and sealed at the surface by the crust, the mantle is as remote as the surface of Mars. "There's never enough data to confirm your world view," notes seismologist Paul Silver of the Carnegie Institution's Department of Terrestrial Magnetism in Washington, "so you have to come up with a vision, an intuition, to direct your research."

In Anderson's case, the beginnings of his vision may go back to his youth and his days of rock collecting up and down the East Coast. He remained close to the object of his affection for some years, first in his heavily geological undergraduate training, then during a year with Chevron using man-made seismic waves to look for oil, and finally, in an indirect way, during 2 years spent drilling and seismically sounding Greenland sea ice to ensure the safe landing of Air Force planes. Given this experience, he was as much geologist as seismologist.

Then, Anderson had his perspective abruptly broadened. The two most powerful earthquakes of the century struck Chile in 1960 and Alaska in 1964. Seismologists got excited as they saw how these shocks set Earth ringing like one planet-size bell. By studying the reverberations of these great quakes, researchers could extract properties of Earth as a whole and layer by layer. Anderson was off on a lifetime of deciphering the nature of the deep Earth.

"I've gotten to think of the earth as my research project," Anderson says. "I don't think of seismology as an end in itself. It's a valid way to ask narrow questions, but I like to use that as a starting point, a first step. I jump around from seismology to petrology to planetary-type things. There aren't very many broad thinkers; that's why I get into trouble."

By the late 1960s, in a bit of broad thinking that has become a cornerstone of the current debate, Anderson suspected that there is a fundamental difference between the upper mantle, which includes the first 600 kilometers or so beneath the tectonic plates, and the lower mantle, where the bulk of Earth's rock is found.

Anderson reached that conclusion in his typically interdisciplinary way. From the composition of available rocks, he inferred a composition for the upper mantle that had given rise to the crust. Then, using lab results and theory, he calculated how seismic waves from earthquakes should behave as they pass through the hotter and more pressurized rock of the lower mantle, assuming it has the same composition as he inferred for the upper mantle.

By monitoring the behavior of seismic waves passing through the lower mantle, Anderson could check whether the properties of the rock there matched his predictions. They did not, leading him to suggest that the lower mantle is denser than the upper mantle and therefore enriched in iron and silicon. In time, that made it seem unlikely to Anderson that the lower and upper mantles could mix; instead, they probably remain layered, like oil over water.

At Caltech Jordan was liberally exposed to this emerging evidence for a stratified mantle, first as an undergraduate student in the mid- to late 1960s and then as a grad student of Anderson's in the early 1970s. As an undergraduate he actually coauthored papers with Anderson on the iron-rich lower mantle. But even then Jordan had his doubts. "Frankly, I didn't give [those papers] much credence," he says. "I didn't think of them as providing strong constraints" on the composition and thus the behavior of the lower mantle.

Both Jordan and Anderson realized that while these papers were the best possible then, they did not prove anything. In time, Anderson's tentative confidence would be reinforced by what he saw as increasing support for a stratified mantle, whereas as Jordan's original doubts would grow. While they worked together, however, their nascent differences went unnoticed as Jordan moved on to his dissertation work. It was not directly related to mantle stratification, a subject that had been out of geophysicists' minds for some years.

The pair's Caltech days may have been serene, but within a few years of leaving in 1972 with his new Ph.D., Jordan was clashing head-on with Anderson. In 1974 Jordan and an undergraduate student coauthored a paper in which they claimed that they could actually see a slab of ocean plate that had sunk at a deep-sea trench into the upper mantle, as in the subduction process of the new theory of plate tectonics, and penetrated into the lower mantle beneath the Caribbean Sea.

In this first study by Jordan of a slab penetrating the supposedly impenetrable boundary, seismic waves passing beneath the Caribbean had revealed a blob of colder rock between depths of 600 and 1400 kilometers. It was detectable because its higher seismic velocity caused waves passing through it to arrive at seismographs sooner than would otherwise be expected. The observed travel-time variations convinced Jordan that the blob "was caused by subduction beneath South America. It got me believing there was, in fact, a large vertical flux between the upper and lower mantle."

In the meantime, Anderson was approaching the slab penetration question in his own way. He asked himself whether slabs of ocean plate that are dense enough to sink into the upper mantle could penetrate all the way into the lower mantle. If any-

Not So Irreconcilable Differences?

Might the disparate views that Don Anderson and Thomas Jordan now have of Earth's deep mantle eventually converge on some middle ground? The history of another of their disputes, this one about what lies immediately beneath the continents, suggests that a rapprochement might someday emerge. In 1975 Jordan had come out with a radically new view of the continents. From observations of the ocean plates, many geophysicists had concluded that the continents were less than about 125 kilometers thick, but Jordan maintained instead that they had central roots extending to a depth of 400 kilometers or more. That's a lot of rock for a continent to be dragging through the underlying mantle.

Jordan claimed that these deep roots were 300° to 500°C colder than rock at the same depth beneath the oceans. But rock at those temperatures would be too dense to stay with the continents, some geophysicists argued. It would fall off and sink away. Jordan had an answer for that criticism, however. The roots do not break away, he argued, because they are made of minerals containing more light chemical elements than are usually found in deep rock. That would compensate for the density increases brought about by low temperatures.

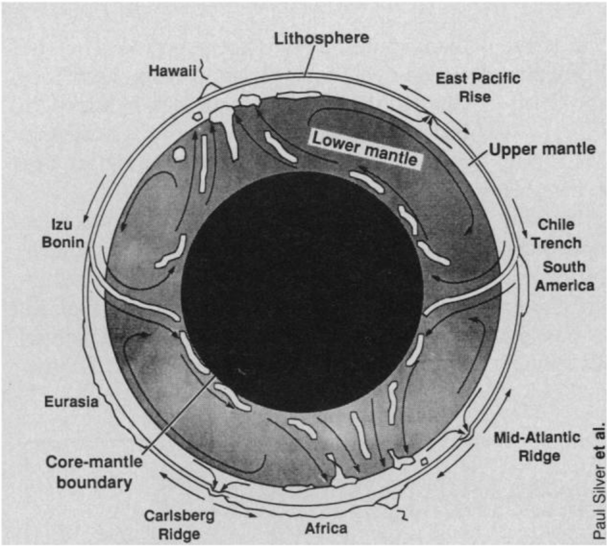
Anderson quickly joined the fray. He and graduate student Emile Okal, who is now at Northwestern University, had been probing the structure of the upper mantle with seismic waves that bounce repeatedly between the surface and the core. This was the same approach that Jordan and his student Stuart Sipkin, currently at the U.S. Geological Survey in Denver, were using to map deep continental roots. But Okal and Anderson said that in their hands the technique showed nothing unusual deeper than 200 kilometers beneath the continents; the central parts of continents seemed not much thicker than the thickest parts of ocean plates, which everyone agreed had no roots.

In Sipkin's words, some "moderately heated discussions" followed. Five years later, this disagreement among seismologists still served as ammunition for those geophysicists who wanted to keep the continents thin.

Now, 15 years after the initial disagreement, Anderson and Jordan do not see eye to eye, but their positions have converged somewhat. For his part, Jordan has pulled back from his contention that the roots must extend to at least 400 kilometers. He puts their depth at between 250 kilometers and a maximum of 400 kilometers. And Anderson, in turn, at least concedes that, like Jordan, he sees seismic perturbations extending down as far as 400 kilometers.

Interpretation of that observation is another matter. Anderson allows that the roots extend to 200 kilometers, a conclusion that Jordan finds gratifying because he now views the means of stabilizing roots below 125 kilometers as the more important part of the debate. But Anderson attributes the seismic anomalies below 200 kilometers not to fixed roots but to cold mantle rock continually sinking beneath the continents. In Anderson's view of plate tectonics, continents collect over such downwellings the way a floating sponge is attracted to a tub drain.

Will Anderson and Jordan's views of the deep mantle also converge, if not merge? If the history of deep continental roots is any guide, another 5 to 10 years of more and better observations and more extensive analysis will be required before the two researchers know whether their findings can be reconciled. ■ **R.A.K.**



Inner Earth. *This view of Earth's interior has slabs penetrating the lower mantle, as Jordan prefers, but with minimal mixing between layers, which is nearer Anderson's views.*

thing could do it, slabs would. They are 100 kilometers thick and stone-cold after 100 million years or so at the surface of Earth, making them by far the densest material in the upper mantle.

To see whether slabs should penetrate, Anderson calculated how the density of the slabs should change as they descend from the surface. In the upper mantle, their minerals are already denser than their surroundings, and they get even more dense as the slabs descend and come under increasing pressure. But they do not become dense enough, according to Anderson's calculations, to continue sinking into the lower mantle. "I've always been impressed with that," he says.

In Anderson's view, the slabs pile up instead in the lower 200 kilometers of the upper mantle, from where they might, if heated sufficiently from below, rise again toward the surface to create volcanoes. "I see no evidence that anything crosses the boundary between the upper and lower mantle" in either direction except heat, he says now. "I think the two are convecting separately. There's always a possibility I'm wrong, but I haven't seen any indication of it yet."

While Anderson was thinking about a stratified mantle, Jordan was getting serious about his hunt for other slab penetrations. In 1977, he got a "beautiful picture" of a slab sinking beneath the Sea of Okhotsk on the northwest edge of the Pacific. It went through the upper mantle, through the boundary, and 300 kilometers into the lower mantle. To image this slab, Jordan used seismic waves coming from earthquakes within the seismically active section of the slab itself.

Jordan thought he had proven his point, but the seismology community took little notice. So in the early 1980s he and his students, Kenneth Creager, now at the University of Washington, and Karen Fischer, now at Columbia University's Lamont-Doherty Geological Observatory, began seismically imaging slabs all around the western Pacific. By the mid-1980s, the Jordan group had detected slabs that were penetrating the 670-kilometer-deep "barrier" by up to several hundred kilometers in several places, including the Kuril-Kamchatka, Japan, Mariana, and Tonga-Kermadec trenches.

Finally people took notice, and among the first was Anderson—who didn't like what he saw. His theme was that imaging Earth is more complicated than Jordan allows. Anderson had learned all about the complications of seismic work during his days on the Greenland ice. Seismic waves behaved differently, depending on their direction, because ice crystals tend to align in a preferred direction. Ice's seismic properties also depended on the abundance of tiny globules of brine trapped in its structure. Like ice, mineral crystals can become aligned and rocks can partially melt to form bits of liquid.

At first, Anderson argued that a preferred orientation of minerals in the slab could have fooled Jordan into thinking he saw a deep extension of the slab. With more time, Anderson and his student H.-W. Zhou did their own slab seismic studies, with ten times as many earthquakes, and reported in recent papers that, among other problems, Jordan had not scanned as widely about the slabs as he should have. There are travel-time variations originating in parts of the mantle beyond subduction zones that are creating a mirage of a slab penetrating into the lower mantle, they say.

Jordan isn't buying these claims of illusionary slabs. "We know about these things. I'm not saying what we've done is completely right, but our techniques are more sophisticated than I've seen [elsewhere] and it all fits together."

Talk of travel times beneath descending slabs could go on indefinitely, but underlying this dispute is a more philosophical debate. Anderson has his doubts about Jordan's seismic studies, but there is more to his resistance. "I could see no way of getting the slab cold enough or dense enough to penetrate deep into the lower mantle," he says. "I think that calculation is sound. Tom could make the same calculation. He will; he's very smart, very broad."

If Jordan has made the calculation, he's not admitting to being impressed with it. He has his own preferences when it comes to scientific evidence. "The most robust constraints are from direct observation," he says, such as the seismic imaging of slabs. "I try not to use laboratory results to draw conclusions about the earth. Don is more confident about that. A lot of arguments for stratification of the mantle say you can't believe what you see." Anderson responds that even the best seismic data cannot stand alone; they provide no unique answer until assumptions are made about the rocks, he says, assumptions that even Jordan must base on theory and lab results.

The few researchers who aren't simply acceding to the "if seismologists of that stature can't decide, how can I?" mentality often lean in Jordan's direction. "I don't know if slabs penetrate or not, but I think Don Anderson's arguments are pretty weak," says Stephen Grand of the University of Texas at Austin, who has done a lot of mantle travel-time work, part of it for his dissertation under another Caltech professor. "He's playing the agitator. He hasn't shown that Jordan has done anything wrong; he just firmly believes that the chemistry is different in the upper and lower mantle, as a lot of geochemists do. Most people believe what Tom has done, but it does not prove anything for sure about deep Earth structure."

So it's a stalemate. Two prominent geophysicists can't agree on what, if anything, 65% of Earth's rocky mass has to do with geology. More than a decade after the first deep-penetrating slab appeared in the literature, seismologists are just beginning to test in a serious way how strong a claim Jordan really has. But seismologists are already receiving data from an expanding worldwide network of new digital seismographs that may help resolve the controversy.

And what do the protagonists see in the offing? Anderson believes he will win in the end. Those opposing him are "all looking at a piece of this thing," he says, instead of the whole; a stratified mantle is supported by a wide array of observation, lab studies, and theory. "I can't think of many people with the whole story; I've got a counter to every one of their arguments. I think they'll eventually come around, but it's slow going."

Jordan, meanwhile, has called it all off. "I've moved on to totally different problems," he says. "I've stopped defending this world view. I'm assuming it's not egregiously wrong and am doing work to carry it farther." In science, as in families, it seems, one's offspring are so hard to bring around.

■ RICHARD A. KERR