Do Plumes Stir Earth's Entire Mantle?

The debate over Earth's inner workings is hardly over, but geophysicists are leaning toward top-to-bottom mixing

Pasadena—HOW DEEP DO THE VOLCANIC roots of Hawaii go? That may sound like an innocent question, but when 125 earth scientists from a range of specialties met here at the California Institute of Technology early this month, that question and its ramifications set off 3 days of sometimes raucous debate. At stake in the discussion were some cherished notions about the deep Earth. Indeed, the Caltech participants brought so many different viewpoints to the topic that the discussion sometimes seemed reminiscent of the six blind men of Indostan, each of whom got hold of a different part of an elephant without being able to grasp the true nature of the beast. In the end, though, an outline of the creature the earth scientists were puzzling over did seem to be emerging.

That creature is the mantle plume, a mushroom cloud of mostly solid, unusually hot rock rising at 10 to 20 centimeters a year from somewhere deep within the planet. In the last 10 years, mantle plumes have emerged as the likely source of the volcanic activity at dozens of hot spots around the globe, including Hawaii, Iceland, and the Galapagos. But the ultimate origin of plumes has remained contentious. Are they contained within the 670-kilometer-thick upper mantle, or do they span the full 2900 kilometers of the mantle? At Caltech's Plume Symposium the decade-long debate seemed to be edging toward an answer: At least some plumes rise from the very bottom of the mantle.

That answer has implications for the nature of Earth's great heat engine, which encompasses plumes and other currents of hot rock in the planet's interior and the motions of surface plates. Many workers have maintained that plumes must have shallow roots, no deeper than the base of the upper mantle—an image in keeping with some researchers' belief that the upper and lower mantle are actually two independently circulating layers, separated by an impenetrable barrier. But others think that plumes rise from the very bottom of the mantle. If so, the mantle would have to be one big bubbling pot stirred through its full depth.

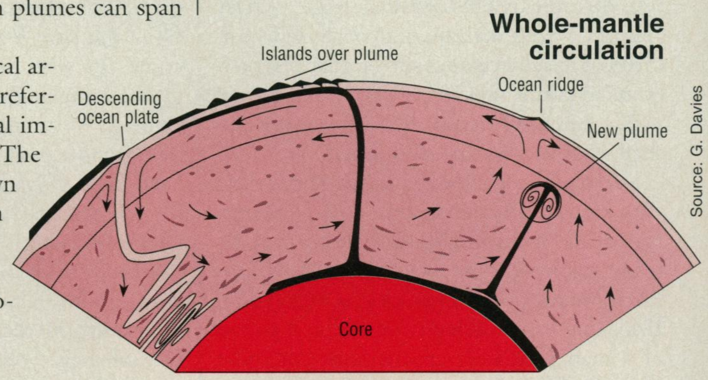
One indication of a trend at the symposium toward deep plumes and a well-stirred mantle came late on the second day, when petrologist Charles Langmuir of the Lamont-Doherty Geological Observatory suggested to those present that the geodynamical evidence seems "pretty compelling" that plumes originate at the very bottom of the mantle. He asked if the parties defending an upper-mantle origin had any response. There was none; Donald Turcotte of Cornell University, the meeting's most outspoken advocate for shallow plumes, was apparently on the golf course at the time. In his absence, it became obvious that many plume researchers accept that at least certain plumes can span the entire mantle.

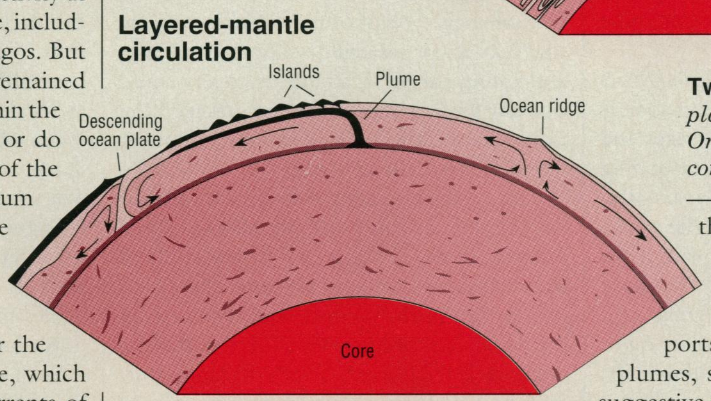
Two of the geodynamical arguments Langmuir was referring to had made a special impression on participants. The first argument boils down to this: Plumes don't seem to carry enough heat for all of them to come from the upper mantle. Geophysicist Geoffrey Davies of the Australian National University in Canberra has argued that if the lower mantle is sealed off from the upper—a picture implicit in the notion of shallow plumes—practically the only way the lower mantle and the core could shed heat would be through plumes originating at the bottom of the upper mantle. By contrast, in a well-stirred mantle—the kind implied by deep plumes—other currents of rock rising from deep Earth could also dissipate some of the heat. All told, according to Davies, plumes confined to the upper mantle would have to carry 70% of the heat from the planet's interior.

The amount of heat in a plume should be evident in the size of the surface bulge that forms when it bangs against the underside of a tectonic plate: the hotter and more buoyant the plume, the bigger the bulge. If plumes are carrying 70% of the heat from the interior, Davies reasoned, each hot, buoyant plume should push up the ocean floor by 2 to 3 kilometers over an area thousands of kilometers across. In fact, though, the world's most powerful plume, beneath the island of Hawaii, raises a seafloor swell of only 1 kilometer. Taken together, the world's plumes—upwards of 40 of them—carry a total of only about 6% of the total heat flow, according to estimates made by Davies and by geophysicist Norman Sleep of Stanford University.

Plumes rising from the bottom of the mantle would carry heat from the core alone, which sheds much less heat than the mantle. In fact, the core is thought to contribute roughly 6% of the planet's total heat—about the amount that seems to be coming up the plumes. That coincidence, combined with the gap between the expected heat transports of upper and lower mantle plumes, struck many observers as highly suggestive of deep plumes. "I'm impressed, as are a lot of geodynamicists, with the ability to explain the topography with [the] heat flow" expected from a mantle that is mixed throughout, said Caltech planetary physicist David Stevenson.

These geodynamical arguments aren't enough to convince every doubter. Turcotte, for one, saw no need to load 70% of the Earth's heat flow onto shallow plumes. "I've corrected you before," he told Davies after his talk, "and I'll do it again. That 70% is utter nonsense, totally fake." According to Turcotte, the slabs of cold ocean plate that plunge into the mantle at ocean trenches would settle to the bottom of the upper





Two choices. *Plumes and sinking plates may span the entire mantle. Or plumes and plates might be confined to the upper mantle.*

mantle and soak up most of the heat rising from greater depths, leaving much less to be carried off by plumes. Davies retorted that the cold slabs couldn't absorb enough heat to save Turcotte's model. "You're wrong," snapped Turcotte. "Right," maintained Davies as he yielded the floor to a chairperson impatient for the next talk.

Even leaving aside the heat-flow data, however, another line of geodynamical reasoning argues against the shallow-plume theory: There may not be enough room in the upper mantle for the largest plumes to form. Geological observations require that some plumes grow to enormous sizes. The plume now beneath the island of Réunion in the Indian Ocean left a trail of volcanic rocks as the overlying plate moved across the plume that can be traced back to the Deccan Traps, a 1-million-cubic-kilometer pile of lava on the mainland of India. Assuming the Deccan Traps formed when the partially molten, bulbous head of the plume first reached the surface, the plume head must have been hundreds of kilometers across. Similarly, the plume that formed the Pacific Ocean's Ontong-Java Plateau must have been at least 800 kilometers across. Such monster plumes would be hard-pressed to fit in the 670-kilometer thickness of the upper mantle.

Indeed, the plumes could not have grown to such sizes unless they originated at great depths, other participants argued. Both theoretical calculations and laboratory experiments, which substitute viscous fluids like corn syrup for flowing rock, suggest that mantle plumes don't spring up fully formed. Instead, they feed on their surroundings as they rise. If plumes started their ascent 2900 kilometers down near the core-mantle boundary, modelers Ian Campbell and Ross Griffiths of the Australian National University told the symposium, they could easily swell to the size needed to feed the Deccan or Ontong-Java eruptions. But a plume that started at a depth of 650 kilometers would still be a puny thing when it arrived near the surface, they said.

The shallow-plume stalwarts had no immediate answer to these objections. Turcotte acknowledged that the tight fit of plume heads in the upper mantle might seem persuasive now, but he told *Science* he has seen equally persuasive evidence come and go during his 25 years in mantle dynamics.

Still, the arguments presented at the symposium mesh with other reasons for thinking many plumes are spawned at the core-mantle boundary. Plumes must be originating from some level in the mantle where heat builds up, making blobs of mantle rock unstable and buoyant. Such a pileup of heat is likely where the highly conductive metallic core hands off heat to the less conductive rocky mantle. What's more, the varied chemical and isotopic compositions of hot-spot rocks suggest that the underlying plumes must originate in a jumble of chemically diverse rock—exactly what seismic studies suggest may lie at the base of the mantle.

But the growing sentiment that plumes can come from the bottom of the mantle is far from hardening into a dogma. Even if deep plumes are becoming part of the standard model of Earth's interior, a lot could still happen to the standard model, as recent developments in seismology attest (see sidebar). And as Kevin Burke of the National Research Council reminded participants in his talk, plumes may come in more than one flavor. Flashing hand-drawn cartoon transparencies, he argued that granting deep roots to some classic hot spots, such as Hawaii, doesn't rule out the possibility that many other hot spots might still be fed from intermediate or even shallow depths in the upper mantle.

Lest researchers become too complacent, they can consult the next-to-last stanza of "The Blind Men and the Elephant," reprinted in the meeting's abstract volume: "And so these men of Indostan/Disputed loud and long,/Each in his own opinion/ Exceeding stiff and strong,/Though each was partly in the right,/And all were in the wrong!" ■ RICHARD A. KERR

New Hints of Deep Slabs

While geodynamicists at the Caltech Plume Symposium debated whether plumes of hot rock rise from the deepest reaches of Earth's lower mantle to the surface (see main text), seismologists remained on the sidelines. But, practically unheralded at the meeting, two groups of seismologists have gathered new evidence that the converse can also happen: slabs of cold rock—erstwhile ocean floor—sinking into Earth's interior sometimes plunge all the way through the upper mantle into the lower mantle. If it holds up, this evidence further undermines the notion that the mantle consists of two layers separated by a virtually impermeable barrier about 670 kilometers down.

The two new studies are based on the seismic equivalent of an x-ray CAT scan, in which earthquake waves diving into the deep Earth along many different paths are used to reconstruct a three-dimensional image of the structures there. These two studies employ the most sophisticated versions of the technique—known as seismic tomography—yet applied to tracing deep slabs. Thanks to the sharp view provided by the latest tomography, Yoshio Fukao and his colleagues at Nagoya University were able to report in a last minute poster at the meeting that they have picked up the ghostly outlines of slabs boring their way into the lower mantle under the western Pacific Ocean. "It now appears obvious that the 670-kilometer discontinuity acts as [only] a partial barrier for slab penetration," they concluded.

The Nagoya group's tomographic views show that slabs beneath Japan, the Southern Kurile region to the north, and the Izu-Bonin region to the south dive into the upper mantle and then flatten out, becoming horizontal near the base of the upper mantle at a depth of 670 kilometers. They then parallel the boundary for as much as 1000 kilometers. But the slab beneath the Java island arc does penetrate the barrier, reaching a depth of 1200 kilometers—albeit only after badly deforming. The picture gets fuzzier in the Northern Kurile and Mariana regions, but there too something slab-like seems to extend as deep as 1000 kilometers.

The second tomographic study, by Rob van der Hilst of Leeds University, Guust Nolet and Wim Spakman of the University of Utrecht, and Robert Engdahl of the U.S. Geological Survey in Denver, seems to confirm that deep slab penetration is a hit-or-miss thing. The group, which sharpened its images by carefully correcting the locations of the earthquakes that served as sources of seismic "x-rays," saw the same pattern of slab deflection and penetration as the Japanese group did. They also report "very good confirmation of deep penetration" in the Northern Kurile region, according to van der Hilst.

It's not the first time that seismologists have seen hints of cold slabs deep in the mantle. A few years ago, seismic evidence suggested that slabs of ocean plate can sink from the surface into the lower mantle (*Science*, 7 February 1986, p. 548), but seismologist Thorne Lay of the University of California, Santa Cruz, told attendees at the Caltech meeting that refinement of those early analyses has eliminated any clear signs of slabs penetrating the boundary. If the evidence of intermittent penetration proves more durable than the earlier claims, the mantle may start looking more complex than advocates of either a two-layer mantle or a mantle that readily mixes from top to bottom have supposed. ■ R.A.K.