Plumes From the Core Lost and Found

The first clear seismic images of deep, rising magma plumes support, in part, a theory under fire

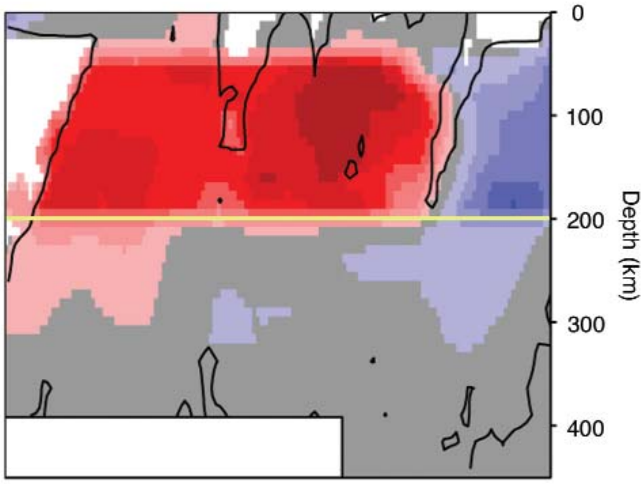
San Francisco—For a 30-year-old unproven hypothesis, mantle plumes have shown remarkable vigor. Most geoscientists assume that the plumes, columns of hot rock rising 2900 kilometers to the surface from the very bottom of the rocky mantle, explain volcanic hot spots such as Hawaii and the great magmatic outpourings of the geologic past called flood basalts. Some have even posited the possible evolutionary effects of plumes spewing such huge eruptions.

No more the cozy comforts of ignorance. Increasingly detailed seismic probing of Earth's interior is forcing geologists to confront some cold, hard truths about these elusive phenomena. Last month, at the fall meeting of the American Geophysical Union (AGU) in San Francisco, scientists reported that not all hot spots have plumes. Some insisted that plumes more than a few hundred kilometers in depth could not form because of the mantle's physical properties. Yet in the face of this assault on the status quo, the meeting also featured striking new evidence of how some hot spots are fed from the deepest reaches of the mantle.

"There was a lot of plume bashing going on" at the AGU meeting, says seismologist Göran Ekström of Harvard University. Don L. Anderson of the California Institute of Technology (Caltech) in Pasadena gave three invited talks and co-authored two more presentations, none of which missed an opportunity to put down plumes. Anderson, a pillar of the geophysics community, believes that the mantle's physical properties preclude the formation of narrow, buoyant plumes in the lower mantle and in fact seal off the mantle below about 1000 kilometers. Instead, he argues, chains of volcanoes like the one anchored at the Hawaiian hot spot could form along a crack in the plate that lets hot mantle rock a few hundred kilometers down rise to the surface and melt.

A case in point seems to be Yellowstone, one of the largest continental hot spots. Two groups of seismologists—Jason Crosswhite and Eugene Humphreys of the University of Oregon, Eugene, and Brian Zurek and Kenneth Dueker of the University of Wyoming, Laramie—reported that they can see no sign that the Yellowstone hot spot is fed from deeper than 200 kilometers, even though they can probe the mantle down to 660 kilometers.

The Oregon group used a standard imaging technique, in which the arrival times of seismic waves from distant, large earthquakes are recorded by scores of seismometers spread across the region. Waves that pass through hotter rock beneath Yellowstone are slowed relative to those encountering only average temperatures. The technique combines the delays of all the waves crisscrossing beneath the hot spot, the way computed tomography forms an image of the body. Although their instrumentation would have allowed them to detect anomalously high temperatures down to 400 kilometers, there were none detectable deeper than about 200 kilometers.



Hot but shallow. Seismic imaging reveals seismically slow and presumably hot rock (red) that has fed the volcanic activity of the Yellowstone hot spot, but no deep plume.

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The Wyoming group used a different technique to look deeper than 400 kilometers. Any deep plume would slice through the two levels at which mantle minerals undergo phase changes—marking the "transition zone" between upper and lower mantle—whose exact depths depend on temperature. If pierced by a deep plume, the transition zone should thin. But although the pair reported that the seismically determined depths to these phase changes undulated across Yellowstone, they found no such thinning. Such results constitute "the first conclusive evidence of the nonexistence of a plume under a classic hot spot," says seismologist Richard Allen of the University of Wisconsin, Madison.

Yellowstone isn't the only place where deep-plume hunters are coming up empty-handed. Jeroen Ritsema of Caltech and Allen have applied the tomographic technique to a set of global seismic observations, paying particular attention to the mantle beneath 45 hot spots on most people's lists. "The relation between hot spots and plumes has been implicit in many people's minds," says Allen, but "it seems clear there is not a plume beneath every hot spot." They have identified only eight plumes going deeper than 200 kilometers.

So where do plumes actually span the mantle? After 4 days of widespread plume bashing at the meeting, seismologist Tony Dahlen of Princeton University delivered an hourlong invited lecture that shored up conventional wisdom on the topic. The work, which involves sharpening up global tomographic images, offers evidence of at least a dozen deep, continuous plumes rising beneath major hot spots worldwide. "People recognize the first images … that are actually convincing," says Dahlen's Princeton co-worker, Guust Nolet. Allen just calls it "the most exciting thing I saw at AGU by a long way."

A key to the Princeton plume imaging was to think of a seismic wave's behavior in terms of a hollow banana rather than just a thin line. Seismic waves actually ripple away from an earthquake in all directions, but for the purpose of analysis, seismologists traditionally consider seismic waves to be a collection of lines or "rays." In conventional analyses, when a ray path passes through a hotter blob of rock, the full slowing of the ray is assumed to be recorded when the wave eventually reaches a seismometer. But, at least in the case of lower-frequency waves passing through skinny blobs like a plume, a ray begins to "forget" its slowing as seismic energy radiates into the ray path from adjacent parts of the wave. Nolet and Dahlen, working with former Princeton postdoc Shu-Huei Hung of the National Taiwan University in Taipei, concluded that a more useful representation would be a hollow banana: most sensitive around a curving ray path (all seismic waves are curved by the deep Earth) but insensitive at its center.

Graduate student Raffaella Montelli of

Princeton used the new technique in analyzing a relatively small but high-quality set of 87,806 seismic recordings assembled by seismologist Guy Masters of the Scripps Institution of Oceanography in La Jolla, California. In Princeton's final global image, the features beneath the classic hot spots of Hawaii, Tahiti, and Easter Island "really are deep mantle plumes," said Dahlen. Some hot-spot plumes, such as those rising to Réunion in the Indian Ocean and the Azores in the Atlantic, actually branch off one of the two huge "superplumes" rising into the lower mantle beneath the South Pacific and Africa (*Science*, 9 July 1999, p. 187).

Not every hot spot has a deep plume in the Princeton tomography, however. Yellowstone is "iffy," says Nolet, and nothing deep feeds Europe's shallow Eiffel plume or Africa's Tibesti hot spot. Absent plumes might reflect patches of sparse data, says Nolet, but "there are a lot of things we call hot spots and associate with plumes that may be shallow."

"It was very impressive," says seismologist Yang Shen of the University of Rhode Island, Narragansett. From the Princeton presentations and his own work with Hung on Iceland data, he finds that the hollow-banana approach improves plume images substantially, up to 100% in the upper mantle beneath Iceland. Seismologist Adam Dziewonski of Harvard was more cautious after hearing the rapid-fire presentations. "I'm usually pretty skeptical when people say they get images of plumes," he says. In the Princeton case, he wonders if they haven't somehow smeared signals from shallow hot rock down into the lower mantle. He's waiting for the Princeton group to complete its testing of the tomography.

Plumes spanning the mantle would have a stimulating effect on a range of earth science. They could clarify how cooling of the interior drives mantle churning. Geochemists would have a better idea of where to locate the mantle's five compartments that store material for up to billions of years. Geologists might better understand the massive flood basalts—thought to spill from the bulbous heads of rising plumes—that dot the globe and are speculated to have overheated climate and triggered extinctions (*Science*, 6 December 1996, p. 1611). Plumes may even shatter supercontinents. Now that would be true vigor.

–RICHARD A. KERR

Physics

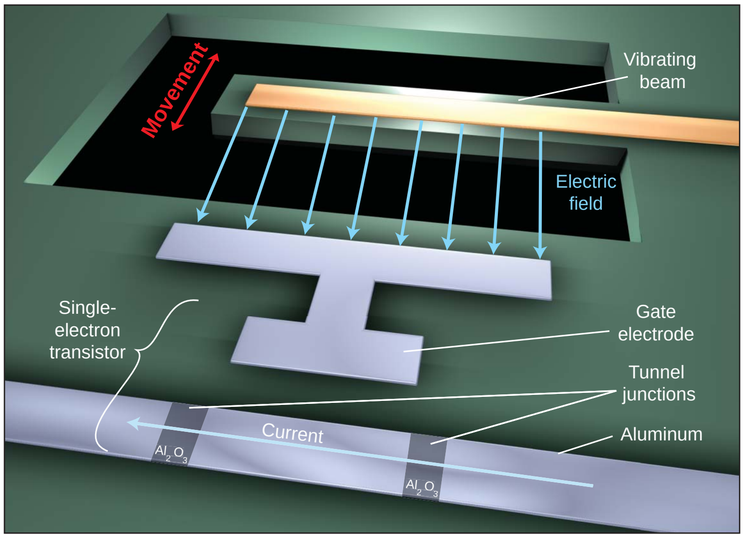
Researchers Race to Put the Quantum Into Mechanics

Machines that make the slightest possible motion could lead to wild new technologies and help reveal why the weird rules of the microscopic realm don't apply to our everyday world

Like fidgety 3-year-olds, tiny objects simply cannot sit still. Atoms, molecules, and other minuscule particles must constantly flit about because of a law of nature that says if you know precisely where something is, you can't know where it's going, and vice versa. The Heisenberg Uncertainty Principle is an unavoidable nuisance; experimental physicists have observed countless times that the smallest bits of stuff in nature wriggle whenever they try to pin them down. However, no one has directly observed the ineluctable quantum quivering—or zero-point motion—of a larger, humanmade object.

That may soon change. Exploiting recent advances in nanotechnology, physicists are racing to fashion vibrating gizmos that can make and measure literally the slightest possible motion. At least four groups hope to reach the quantum limit of motion within months. The feat could open the way for tiny, fingerlike force detectors with the highest possible sensitivity, says Andrew Cleland of the University of California (UC), Santa Barbara. Such detectors might enable researchers to quickly decode DNA and other large molecules, and someday they might serve as the guts of superfast quantum computers.

Quantum machines might even help solve a conundrum as old as quantum mechanics itself: Why can a tiny object like an electron be in two different places at once, whereas a big thing like a pencil or a person cannot?



Shaky connection. Movement of a nanometer-sized beam changes the voltage on the gate electrode of a single-electron transistor, which changes the current running through the transistor, which reveals the motion.

ILLUSTRATION: C. SLAYDEN

"We don't see quantum behavior in our macroscopic world, so in some sense we're protected from quantum mechanics," says Miles Blencowe, a theoretical physicist at Dartmouth College in Hanover, New Hampshire. "What protects us?" To find out, he says, experimenters might try putting progressively bigger mechanical devices into here-and-there "superpositions" to observe what, if anything, goes wrong.

First, though, physicists must reach the quantum limit of mechanical motion. That will require overcoming serious technical challenges, says Michael Roukes of the California Institute of Technology (Caltech) in Pasadena: "This is just damned hard stuff to do."

A subtle vibe

The biggest hurdle is heat. Thermal energy makes large objects wiggle, and at any achievable temperature those vibrations overwhelm the zero-point motion. For example, according to quantum mechanics, a tuning fork can gain or lose energy only in discrete dollops whose size is proportional to the fork's frequency of vibration. Because the frequency is low (440 cycles per second for concert-pitch A), each quantum of energy is so small that the fork contains billions of them even at a degree above absolute zero. To suck out enough of them to see the zero-point motion, the fork would have to be cooled to a few billionths of a degree.

Or an experimenter could