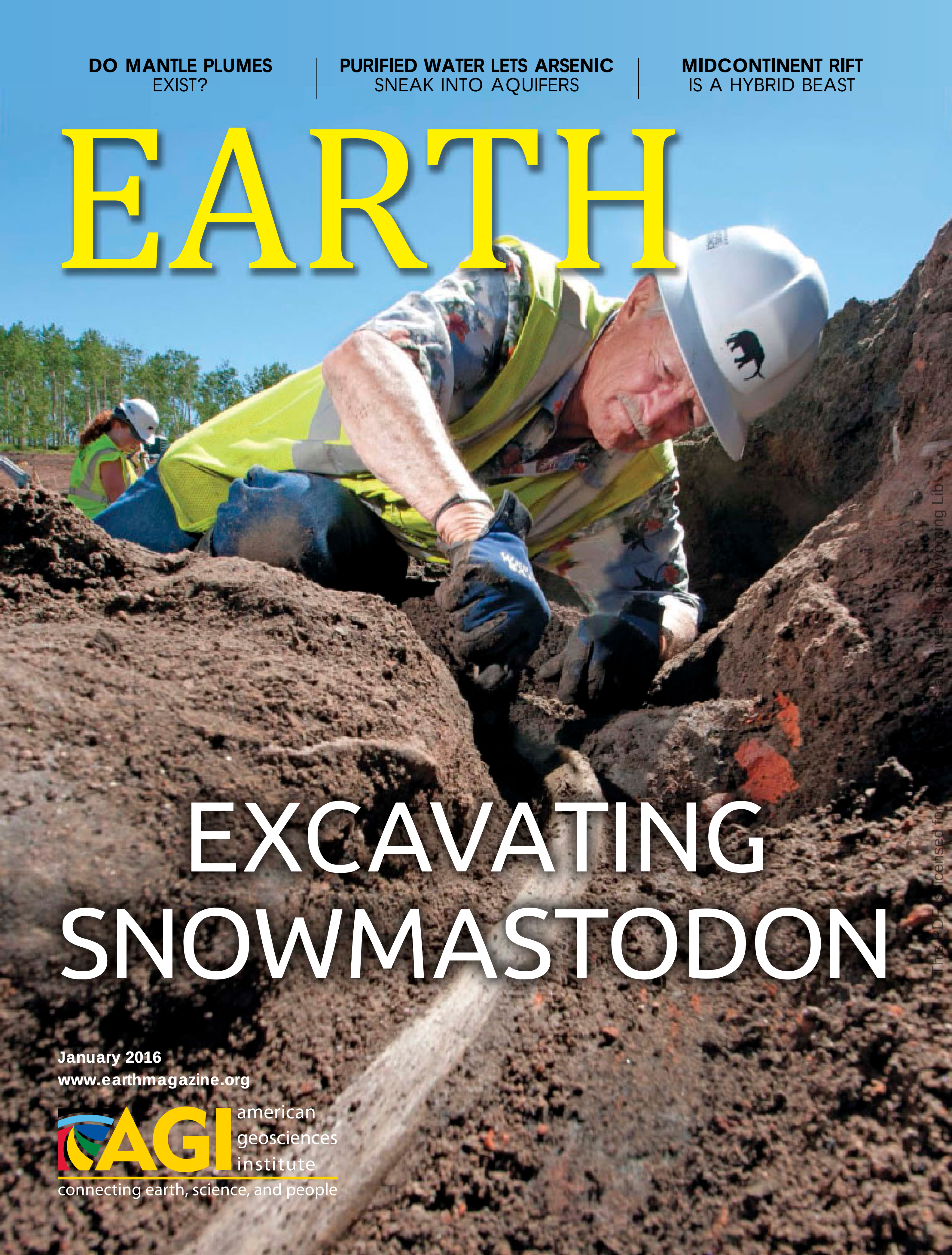

DO MANTLE PLUMES EXIST?

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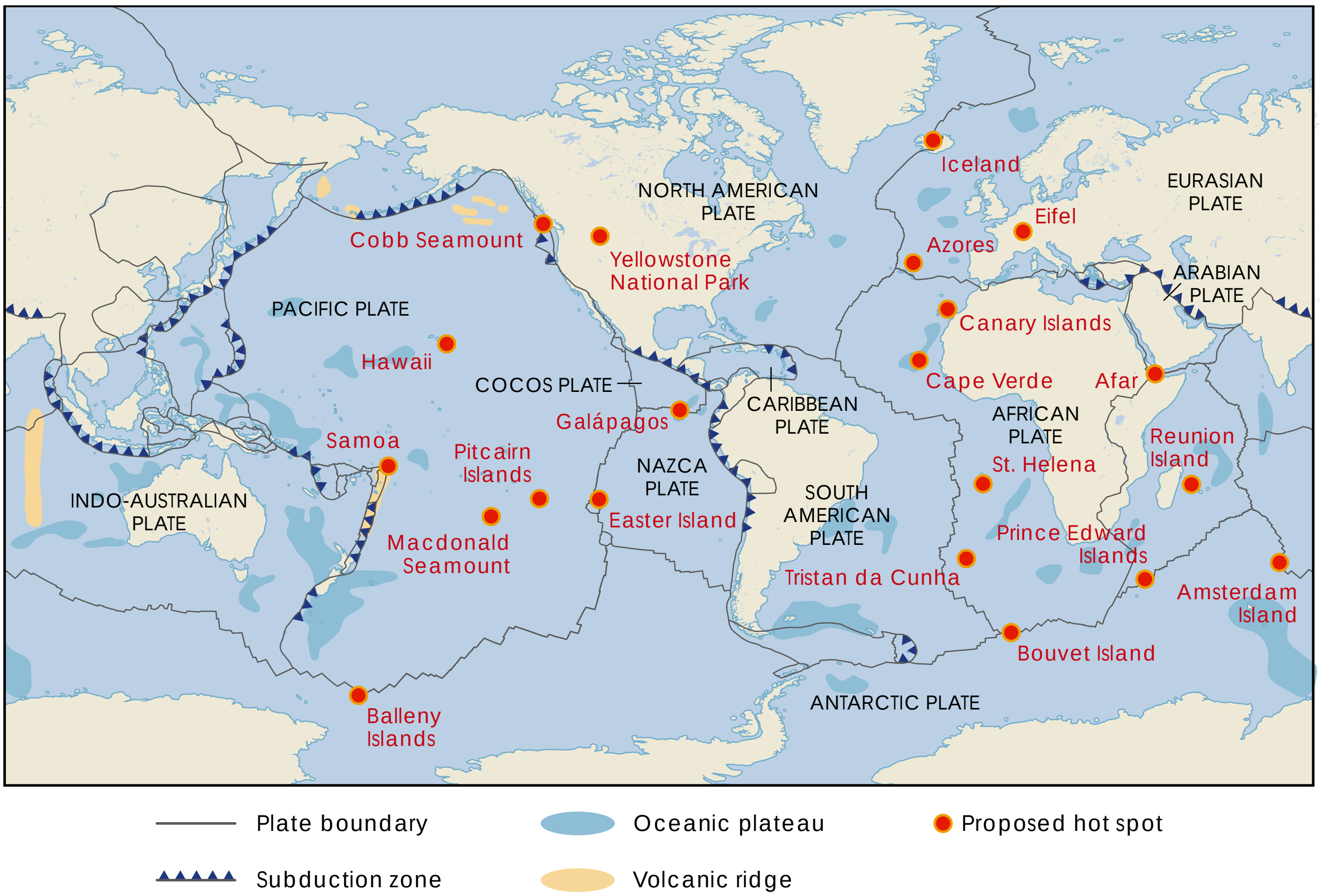
THE QUESTION OF MANTLE PLUMES

Sara E. Pratt

In 1963, J. Tuzo Wilson first proposed that volcanic chains like the Hawaiian Islands form when a tectonic plate drifts over a "hot spot" in the mantle. Eight years later, Princeton geophysicist W. Jason Morgan suggested that such hot spots — he initially proposed about 20 around the world — were fueled by narrow plumes of hot mantle rock rising from the core-mantle boundary.

Since 1971, the plume hypothesis, although never universally accepted, has become the most widely held explanation for so-called anomalous volcanism — the type that occurs far from plate boundaries, like in Hawaii and Yellowstone, or in excessive amounts along mid-ocean ridges, as in Iceland. In addition to Hawaii, Yellowstone and Iceland, other notable examples include Pitcairn Island, Macdonald Seamount, the Galápagos Islands, the Azores, the Canaries and the Afar region of Africa.

Over the years, the hypothesis has continued to be debated and studied, resulting in thousands of journal articles. Many of these have described significant variations on the original hypothesis, yet still refer to "plumes" as the underlying phenomenon, which has introduced an element of semantics to the debate (see sidebar, page 40). Other researchers



Over the years, many different locations have been proposed as hot spots. Some of the most well-known proposed sites are labeled with red dots in this diagram, which also depicts the borders of Earth's tectonic plates.
Credit: K. Cantner, AGI

suggest plumes are not required at all to explain anomalous volcanism. They instead propose a "plate hypothesis" in which lithospheric stretching allows already melted rock to escape from the mantle to the surface.

Despite the debate, Morgan's hypothesis, in nearly its original form, has become entrenched in undergraduate and high school curricula. But although the elegant explanation — often demonstrated with common household items, like a pencil or a candle being used to punch or burn through a piece of paper — has fascinated generations of students, the difficulties of confirming such a hypothesis and the intricacies of the ongoing debate are rarely included in the lesson.

If the vast body of mantle plume research has done nothing else, it has revealed the difficulties inherent in trying to plumb the depths of Earth's interior. Reaching to a depth of 2,900 kilometers, the mantle cannot be sampled by fieldwork; it must be remotely sensed and modeled. What little we know about the mantle's composition and structure has been gleaned from geochemical analyses of deep-sea lavas or the rare chunk of exhumed mantle rock, and from interpretation of seismic waves that have traveled through the deep Earth.

The invention in the late 1970s and early 1980s of seismic tomography — the use of earthquake seismic waves to image the three-dimensional structure of the mantle, much like X-rays are used to produce medical CT scans of the human body — offered a promising path toward understanding the core-mantle boundary in more detail. But the method has so far proven to be of limited use when it comes to visualizing small-scale features, as plumes are assumed to be. However, new models of the mantle that rely on the immense number-crunching capacity of supercomputers may offer the clearest picture yet and move the mantle-plume debate forward (see sidebar, page 40).

A Textbook Case?

Morgan proposed his hypothesis in the wake of the plate tectonics revolution, when geologists were still struggling to explain anomalous volcanism. Most of Earth's volcanism occurs on plate boundaries: on mid-ocean ridges or above subduction zones, like those that surround the Pacific Ocean in the so-called Ring of Fire. But the cause of volcanism far from a plate boundary was a conundrum.

In Morgan's conception, plumes were chimneys of warm, buoyant rock about 100 to 200 kilometers wide that were rooted at the core-mantle boundary. These narrow conduits of deep-mantle material rise through the solid mantle before spreading out laterally, like a thunderhead, in the upper asthenosphere — the ductile zone of the upper mantle that lies below the brittle lithosphere. From there, they can cause the lithosphere to swell and shear, disgorge massive flood basalts, and form age-progressive volcano chains.

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In addition to having deep roots and high temperatures relative to surrounding mantle rock, Morgan's other fundamental criteria were that plumes transport primordial mantle material from below the zone of active convection; are fixed relative to one another; produce time-progressive volcanic chains; break up continents; and drive plate tectonics.

Morgan formulated his hypothesis around the formation of the Hawaiian Island-Emperor Seamount chain in the middle of the Pacific Plate. The islands and seamounts exhibit age progression, with the youngest near present-day Hawaii and the oldest near the Aleutian Trench, which Morgan suggested was indicative of a plate moving over a stationary hot spot. The bend in the chain, he suggested, indicated that the Pacific Plate changed direction roughly 47 million years ago.

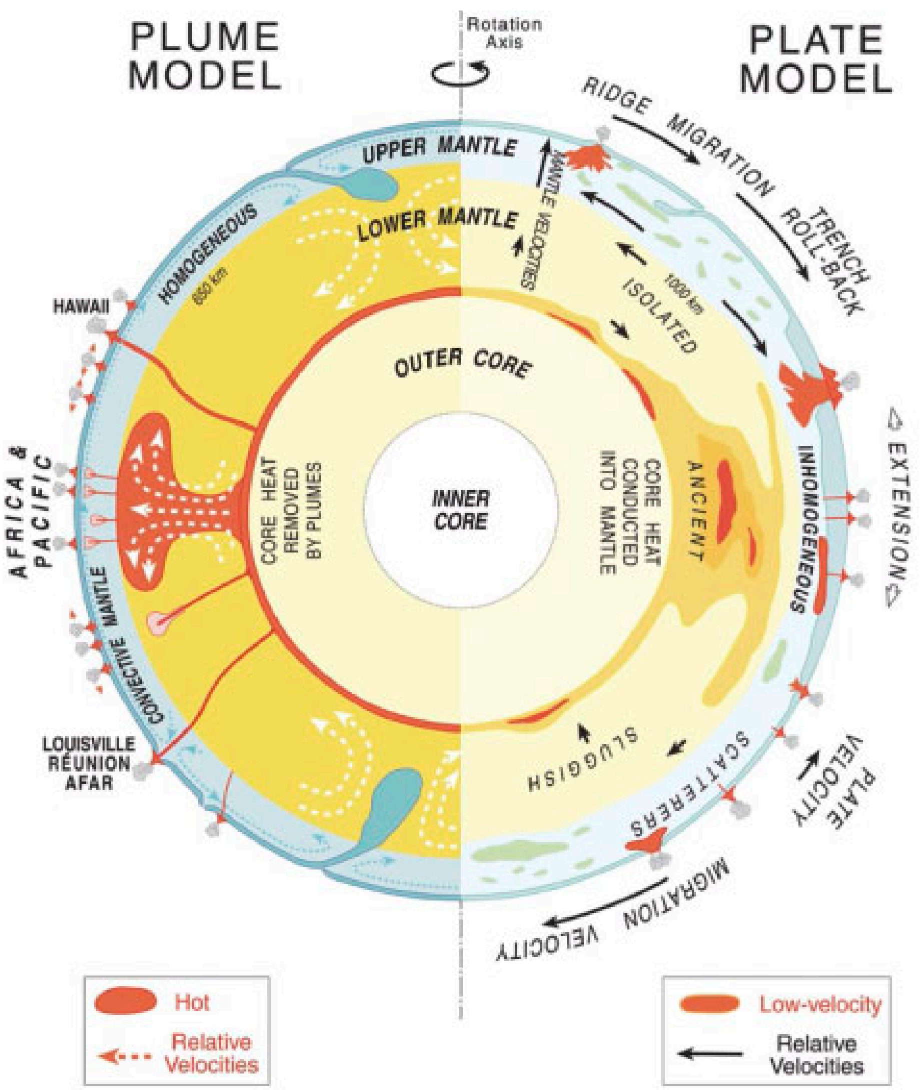
The island chain became the textbook example of a mantle plume hot spot. And, confirming the existence of a plume beneath Hawaii thus became something of a holy grail for mantle researchers.

Can We See the Mantle?

In the late 1970s and early 1980s, some measurements of ratios of helium-3 to helium-4 in Hawaiian basalts and elsewhere were discovered to be much higher than those in mid-ocean ridge basalts. Because most helium-3 was formed at the same time as Earth about 4.5 billion years ago, it is called a "primordial" isotope. It is depleted in surface material because helium escapes into space. Thus, the high ratios in Hawaiian basalts were interpreted as evidence that plumes are fed by primordial material from deep in the mantle, while mid-ocean ridge systems tap recycled upper mantle material depleted in helium-3.

Beginning in the 1980s, seismologists, led by Adam Dziewonski at Harvard, began developing new techniques that took advantage of new computing capacity and technologies like digitization to build upon earlier efforts to use earthquake seismic waves to image the three-dimensional structure of Earth. Dubbed "teleseismic tomography" by Dziewonski and the late Caltech seismologist Don L. Anderson in 1984, the new technique was soon applied in mantle plume studies.

Seismic tomography works by measuring the travel times of earthquake waves as they arrive at various stations around the world. Waves travel faster through cool rock than through warm rock. Thus, faster travel times are assumed to indicate zones of relatively cool, high-density rock that is sinking in the mantle, whereas low-velocity zones are interpreted to indicate hot, low-density rock that is rising, like mantle



A schematic cross-section of Earth showing the plume hypothesis versus the plate hypothesis.
Credit: Anderson, GSA Special Papers 388, 2005

plumes would be. Researchers translate these into maps of zones of upwelling and downwelling, which could help improve our view of Earth's interior and answer longstanding questions about the convection cells that drive plate movement — including whether the whole mantle convects or just the upper mantle.

But there is a major drawback in correlating seismic wave speeds with rock temperature: Mineralogical and chemical differences in a rock's composition can also affect seismic velocities, as can the presence of partially melted rock. Determining whether low-velocity zones represent thermal, physical or compositional differences in the mantle has become a debate of its own.

One of the largest low-velocity zones rises diagonally from beneath the southern tip of Africa toward the Afar region of northeast Africa; formally called a large low-shear-velocity province, it is better known as a "superplume." There is another similar zone under the Pacific. But whether such regions slow seismic waves because they are hot, or just compositionally different than surrounding mantle rock, cannot be determined by tomography.

"These methods reveal the seismic structure of the mantle," says Gillian Foulger, a geophysicist at Durham University in England, and a longtime collaborator of Anderson's. They "do not reveal the geological structure. The two are not the same."

Seismic tomography has other limitations as well. Seismic wavelengths are long and plumes are thought to be quite narrow, thus making their detection challenging. Additionally, if seismometers are closely spaced in an array, the aperture of their "view" down into the earth is narrowed. This can be problematic on ocean islands like Hawaii and Iceland, which have limited land area on which to deploy seismometers.

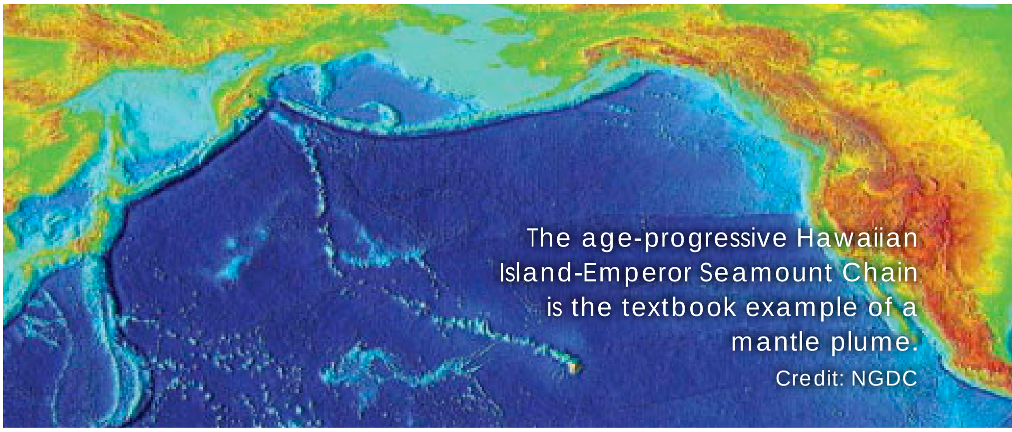
In the late 1990s and early 2000s, several projects — among them SWELL (Seismic Wave Exploration of the Lower Lithosphere) and PLUME (Plume-Lithosphere Undersea Mantle Experiment) — deployed ocean-bottom seismometers in an attempt to answer questions about the structure of the lithosphere and mantle beneath Hawaii. But the plume studies came to various, often conflicting, conclusions. Some critics of the plume hypothesis question if Hawaii was formed by a plume at all, suggesting instead that it could have resulted from purely lithospheric processes.

Do Plumes Exist?

One of those critics was Anderson, who in the early 2000s, along with dozens of like-minded colleagues including Foulger, laid out the alternative plate hypothesis, which they proposed was more consistent with the bulk of observations collected to date.

Although Morgan initially presented mantle plumes as an assumption, over time, the fact that they were an assumption — not an observation — has been forgotten, Foulger says. No plume has yet been found to satisfy all the criteria currently attributed to plumes, she says, adding that the hypothesis has become too flexible, with ad hoc variations tacked on to accommodate any finding.

For example, in the 1990s, petrological and geochemical analyses revealed that basalts of suspected plume origin displayed a much wider range of geochemical



signatures than initially thought, including helium isotope ratios in the range of depleted shallow mantle or lithospheric material. This prompted plume-hypothesis supporters to suggest that the source of the depleted plume material could be subducting slabs of upper mantle sinking into the deep mantle and becoming incorporated into preexisting plumes.

When paleomagnetic analysis revealed that volcanism at the Hawaiian hot spot had migrated and changed direction over the course of its existence, and is therefore not fixed, some researchers proposed that plumes are distorted by convection in the mantle and thus would not be where expected. Such "mantle wind" was also invoked to explain the bend in the Hawaiian chain and the lack of age progression in other island chains.

"Plumes have been proposed to come from almost any depth, to rise vertically or tilt, to flow for long distances laterally, to have narrow or broad conduits, to have no plume head, one head, or multiple heads, to produce steady or variable flow, to be long- or short-lived, to speed up or slow down, to have a source that is either depleted, enriched, or both, and to have either high or low [ratios of helium-3 to helium-4]," Foulger wrote in Geoscientist in May 2003.

She wasn't alone in her thinking that the hypothesis was becoming too broad. In a letter to the editor of Geoscientist that year, Northwestern University seismologist Seth Stein wrote: "I wouldn't blame anyone for the state of thinking … about hot spots and mantle plumes except ourselves. As in Pogo's dictum, 'We have met the enemy and they are us.'"

Stein added that in the "absence of any other clear model," the geoscience community had accepted "very vague ideas about plumes" and allowed them to become the "null hypothesis" for anomalous volcanism. He noted that although the hypothesis initially entailed rigorous criteria — for example, the presence of a low-velocity zone, age-progressive island chains and near-fixity — the science had progressed to the point where "plumes don't have to meet any particular test."

"Hence the hypothesis now always works with appropriate site-specific modifications, but increasingly doesn't tell us anything or predict anything, especially about structures formed in the past," he wrote. "It does, however, make it harder to offer nonplume explanations."

In the mid-2000s, several researchers attempted to start fresh, laying out a new definition of a plume as a thermal instability with a large, bulbous head that is heated by the core, arises from the bottom of the mantle and is followed by a narrow tail. But many of the same issues remain.

A Plate Explanation for Hawaii?

One of the main points raised by critics of the plume hypothesis is that it requires that two independent types of thermal convection be operating in the mantle — one associated with plate tectonics and the other causing hot spot volcanism. It is much more likely, they say, that only one type — that associated with plate tectonics — is at work, and it wouldn't produce narrow upwellings.

In 2014, Anderson and James Natland, a geochemist at the University of Miami, wrote in Proceedings of the National Academy of Sciences that Archimedes' principle of buoyancy and the laws of thermodynamics dictate that, in a cooling planet, "convection is composed of narrow downwellings and broad upwellings, the precise opposite of assumptions" in the mantle plume model. "Hot spots such as Hawaii, Samoa, Iceland and Yellowstone are due to a thermal bump in the shallow mantle, a consequence of the cooling of the Earth."

The two theories thus differ on the source of the magma at sites of anomalous volcanism. Instead of deep-mantle material being drawn to the surface, the plate hypothesis holds that the chemistry and volume of lavas are dependent upon the local mantle rock type and its ability to melt. "The asthenosphere is mostly near its solidus temperature, hence it is widely capable of melting wherever it is depressurized by extension," says Warren Hamilton, a geophysicist at the Colorado School of Mines in Golden, Colo.

Hawaii is a perfect example, Hamilton says. Rather than the result of a mantle plume, it is a propagating extensional crack in the middle of the Pacific Plate, which is subducting under Japan in the west and diving under the Aleutian Islands in the north faster than it is spreading at the East Pacific Rise. "The Hawaiian-Emperor southeastward-advancing crackspot is a product of the extensional stresses near the midline of the North Pacific between subduction under Asian systems on one side and American ones on the other," he says.

It's no coincidence, he adds, that the famous dogleg bend in the Hawaiian-Emperor chain — formerly attributed to a sudden 60-degree change 47 million years ago in the direction of the plate as it drifted over a hot spot — crosses the Mendocino Transform Fault.

"This fault marks a change of 30 million years in the age of the lithosphere, which represented a huge step in thickness and properties ... 47 million years ago," he says. "This requires that the change [that created the bend in the chain] was controlled from the top, not from Earth's core."

In an essay published on mantleplumes.org, the website maintained by Foulger to track materials and publications related to the plume debate, Hamilton and Anderson called the plume hypothesis "zombie science" — a hypothesis that, despite contradictory evidence and the lack of supporting evidence, will not die.

Mantle plumes have become dogma that few researchers are willing to contradict in a publish-or-perish environment, Hamilton says, especially in times of tightening budgets. Those who should be questioning it are the "young Turks," he says, but first they, and the general public, have to learn that there are alternatives to what they may have learned in school.

How Are Plumes Taught?

At many colleges and universities, especially in entry-level geology courses, the classic model has long been predominantly taught. This trend remains largely intact, although at least some say they're presenting it increasingly as unsettled science.

"We touch upon [the plates versus plumes controversy] a bit in my upper division classes, but it is never debated as such. So, I present hot spots as plumes from the deep mantle," says igneous petrologist Erik Klemetti, an assistant professor at Denison University in Granville, Ohio. "As for how deep, I say that's still being debated."

Maya Tolstoy, a marine geophysicist and associate professor at Columbia University, says that she also doesn't touch on the debate in her introductory classes. "I talk about decompression melting at ridges, mantle convection pulling the plates apart, and Hawaii as a classic hot spot. I do mention that the concept of hot spots being fixed points is an assumption that is not always agreed upon or necessarily reliable. Personally, I also am not surprised that things are a little more complicated in how the melt finally makes its way to the surface than the simple 'cartoon' models. But I'm not sure that the complexity of the real world negates the basic model."

Kevin Stewart, a structural geologist and associate professor at the University of North Carolina at Chapel Hill, teaches that aspects of the plume hypothesis are being debated and raises some of the possible alternatives. "I do talk about the idea that hot spots may represent a fixed reference system and one way people explain this is with plumes originating from the core-mantle boundary," he says. "But then I present some seismic tomography data that show that the cartoon images of a thin, rising column of hot material traversing the entire mantle don't really match a lot of the tomography."

In discussing Hawaii, Stewart says, "I talk about the possibility that if the melt at Hawaii is being generated at shallower levels in the mantle due to plate tectonic processes, like the shearing of the asthenosphere, then there are other ways to explain the bend. But I don't go into it too deeply. The whole story behind a plate origin for hot spot volcanism is pretty complicated and the full explanation is far beyond the scope of my 101 class."

At Northwestern, Stein teaches his introductory geology students that the plume hypothesis for the age-progressive Hawaiian Islands is an "attractive" explanation for mid-plate volcanism but it remains "controversial" since the data don't always match some predictions. He says he tells students it's still unclear whether hot spots are caused by plumes located as deep as the core-mantle boundary or by localized upper-mantle volcanism, or by either of those processes operating at different locales. "I suspect how people address the topic in class varies depending on teaching philosophy — some of us try to discuss unresolved topics to motivate young people into the science," Stein says.

"After all, if everything's known, why go into it?"

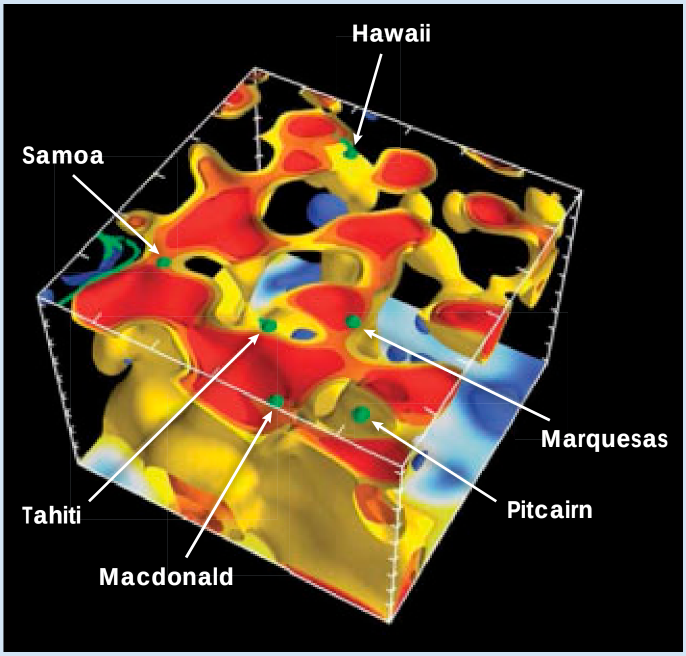
Pratt is the senior editor of EARTH.

What Lies Below?

Technological advances continue to improve the resolution of our view of Earth's interior, but disagreement remains over what we're viewing. In a recent Nature paper titled, "Broad plumes rooted at the base of the Earth's mantle beneath major hot spots," Scott French, a computational scientist at the Department of Energy's National Energy Research Scientific Computing Center at Lawrence Berkeley National Laboratory, and Barbara Romanowicz, a seismologist at the University of California at Berkeley, reported the development of the most detailed model yet of the structure of the mantle.

The three-dimensional tomographic model, similar to a medical CT scan, revealed large swells of what is likely hot mantle material with diameters roughly 1,000 kilometers wide. The structures, dubbed plumes by the researchers, rise from areas at the core-mantle boundary with strongly reduced seismic velocities, which are embedded in larger zones with anomalously low velocities that are up to 5,000 kilometers wide.

"Previous tomographic models have hinted at the existence of plumes, but it was hard to say unequivocally that they were



Scientists using a new tomographic model of Earth's mantle have identified 5,000-kilometer-wide swells of potentially hot material in the lower mantle that the researchers say confirm the existence of plumes.
Credit: French and Romanowicz, Nature, 2015

there," French says. "With our model you can say 'Yes, that definitely is a plume.'"

In the model, plumes were identified under Hawaii and Iceland but not beneath Yellowstone. A few of the structures seen in the model rise into the upper mantle — beneath Pitcairn Island, for example — but most do not get above depths of 1,000 kilometers.

"They start to thin out in the upper part of the mantle, and they meander and deflect," Romanowicz said in a statement released with the new study. "So while the tops of the plumes are associated with hot spot volcanoes, [the larger plume bases] are not always vertically under [the hot spots]."

French says the remnants of the plumes in the upper mantle "would be too narrow for us to see, even with the techniques we use, which are limited in local resolution due to the fact that we are imaging the whole mantle."

Applying Supercomputers to Seismograms

This new view of the structure of Earth's mantle arose from a model that French and Romanowicz developed using wave-form inversion — which, like typical seismic tomography, is based on a technique similar to the statistical regression used to best fit data points to a line or curve. But their model differs in how it makes use of seismic data.

"The difference between what we do and what most other researchers do," French says, "is that instead of using the arrival times of specific seismic waves as our data, we use the entire seismic wave-form record."

The researchers used 3 million hours of supercomputer time (with many processors running in parallel) to hone their model of the fast and slow regions, which are interpreted as warm and cool areas, of the mantle until the model was able to accurately simulate seismogram outputs that matched the real-world results from 273 strong earthquakes that occurred over the past 20 years.

Previous tomographic models faced computing limitations that required simplification of the physics to the point that information was lost, French says. "Supercomputing allows us to treat the physics more exactly so we can get around these traditional impediments."

But whether the plumes actually represent temperature differences and show convection remains unknown. The standard seismological view is that low shear-wave velocities indicate hotter material, French says, but they can also be caused by compositional differences, which would also explain the plumes' vast widths and long-term stability.

A Plume by Any Other Name?

The new study emphasizes the role of language in the plume debate, which is no stranger to semantic arguments. As early as 1973, just a few years after W. Jason Morgan first suggested mantle plumes, one researcher sought clarification on how plumes differed substantially from the normal convective models already suggested by plate tectonics, writing: "It would be most helpful if someone would explain in terms that are meaningful to geophysicists in what respects the conventional geological pictures of rising magma differ from 'a thermal plume.'"

While what French and Romanowicz have found may not sound like a traditional plume, French says the structures they identify may be related to large low-shear-velocity provinces, also called superplumes. "Those [low-velocity zones] are in close juxtaposition to where we see these plumes," he says, "but the plumes are anchored near the edges of those zones."

New models like French and Romanowicz's might help researchers begin to reconcile what we see on Earth's surface with what we can know of its interior. And, in the future, perhaps further technological advances will help change the language of the debate itself.

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