A window on the inner Earth

Seismic studies of the deep roots of Hawaii's volcanoes may help to reveal mysterious circulation processes in the Earth's mantle — shedding light on our planet's history and dynamics. Rex Dalton peers beneath the surface.

For most of us, the Hawaiian Islands are a holiday hotspot, a haven for sun and surf. But for Earth scientists, the archipelago's real appeal lies in the geophysical hotspot that lies beneath the islands and is responsible for their formation.

Next autumn, a multi-institutional team will encircle Hawaii with an array of seabed seismometers to study the hotspot's roots deep within the Earth's mantle. The $2.5-million project, backed by the US National Science Foundation (NSF), is called PLUME, for Plume-Lithosphere Undersea Melt Experiment. By recording seismic waves from distant natural earthquakes, researchers hope to chart the hotspot's plumbing — and in doing so address fundamental questions about the processes that have shaped, and continue to shape, our planet.

Much of the Pacific Ocean's sea bed is a single plate that, over the past 70 million years, has drifted slowly northwest relative to the layers beneath it. The hotspot is the result of a rising plume of hot buoyant rock, which deforms the overlying tectonic plate and spreads out beneath it. As the plate has slowly moved over the plume, this has created a huge plateau, or 'swell', some 2,000 kilometres long and half as wide (see Diagram, opposite).

The solid rock rising up through the plume is released from the enormous pressure of the Earth's interior and starts to melt. This in turn melts some of the overlying plate, or lithosphere, and the resulting mixture can then seep through cracks in the plate, giving rise to volcanoes. The plate's movement has produced a string of volcanic islands stretching away from the hotspot. Today, the plume is centred to the southeast of Hawaii's Big Island, near the Loihi seamount, an undersea active volcano.

The volcanic processes that gave rise to the Hawaiian Islands are relatively well understood. But the plume that feeds the hotspot remains shrouded in mystery. Researchers want to know the plume's width, the temperature of the rock rising up through it, and more about its geochemical composition. Most fundamentally, they want to know how deep in the Earth's mantle are the plume's origins. "The mantle has been like a mysterious black box," says Naomi Oreskes, a geologist and historian of Earth science at the University of California, San Diego. "Finally, technology is allowing the opening of that box."

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Chain reaction: the Hawaiian Islands stretch away from the geophysical hotspot that formed them. Currently, the hotspot is centred just southeast of the Big Island (bottom right).

Core issues

Long-lived hotspots such as that beneath Hawaii — others underpin Iceland, the Galapagos Islands and the Cape Verde Islands, west of Africa — are believed to depend on stable plumes that arise from convection currents originating deep within the mantle. But it remains unclear from what depth the plumes arise. They may have their roots in the upper mantle, less than 660 km below the surface. But if their origins go deeper than this, as many geophysicists believe, then they probably come from about 2,900 km, at the boundary between the lower mantle and the seething cauldron of iron-rich material that forms the Earth's core.

For geophysicists, the plume's depth is an important issue. Leading models of the circulation of material in the Earth's mantle — which drives the movement of the lithosphere's tectonic plates — result in plumes transferring material across the boundary between the upper and lower mantle, at a depth of 660 km. But at this point, hot rising minerals undergo a phase transition that results in a decrease in temperature and therefore a decrease in buoyancy. Some geophysicists speculate that this may be sufficient to prevent hot rock, rising from the core–mantle boundary, from punching straight through to the upper mantle — so they argue that hotspots observed at the Earth's surface must have a shallower source.

If plumes do not traverse the transition zone at 660 km, it would also hinder researchers interested in the lower mantle's composition — which, in turn, informs our understanding of how the planet formed and has evolved over the eons. Geochemists have made inferences about the Earth's deep interior by analysing material that has reached the surface in volcanic eruptions over long-lived hotspots. If none of this material comes from near the core–mantle boundary, they will have to revise their ideas.

PLUME should remove these unknowns by providing the best picture yet of the 660-km transition beneath a hotspot — and so it will be watched keenly by Earth scientists worldwide. The project is significant also because it represents the most ambitious deployment of undersea seismometers yet attempted. "This experiment will be used as a way to rethink what marine seismology is all about," asserts Gabi Laske, a seismologist at the Scripps Institution of Oceanography in La Jolla, California, and a principal investigator for PLUME.

Action stations

In September, the research vessel *Roger Revelle* will deploy the first PLUME instruments, placing 35 seismometers on the ocean floor at depths of 4–6 km. For the first 15 months, the seismometers will be placed some 75 km apart, surrounding the Big Island. During the second 15-month deployment, the array will be enlarged around the entire Hawaiian Island chain, with the instruments set some 200 km apart. A further 10 seismometers will be placed on the islands themselves throughout the project.

The seismometers will record the precise timing and amplitudes of seismic waves. For instance, if an earthquake occurs in Tonga — some 5,000 km south of Hawaii — PLUME's instruments will pick up the seismic waves as they ripple through the Earth. The timing of their arrival at Hawaii is crucial: by knowing exactly when the wave arrives at each seismometer, researchers can determine the speed with which the waves propagated through the region below the seismic array. With this information, the team will infer what the waves passed through — for example, seismic waves move more slowly through hot rock than through cooler material.

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By combining information from many earthquakes, PLUME investigators will draw up a three-dimensional picture — in much the same way that X-ray images are combined to form the familiar three-dimensional computerized tomography scans used in diagnostic medicine.

The PLUME team members believe that clustering their seismometers as proposed will produce a detailed picture of the plume down to almost 700 km. If it extends to these depths without widening substantially, the experiment would provide some of the strongest evidence yet that it emanates from within the lower mantle, most likely the core–mantle boundary.

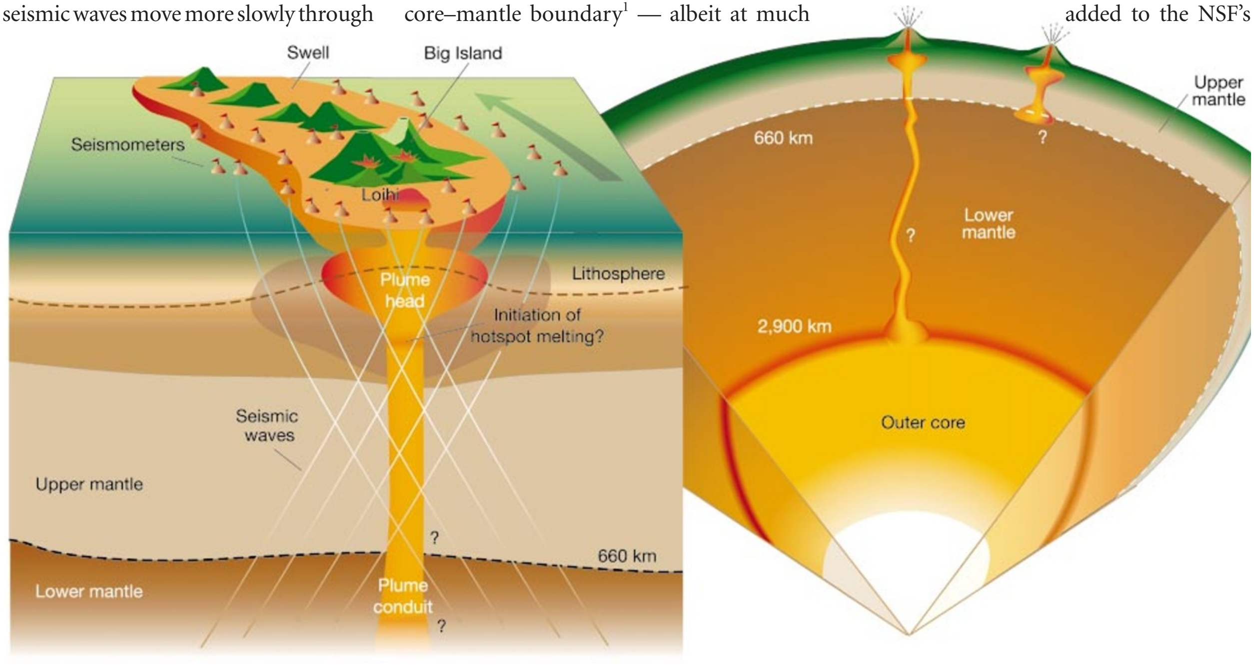
Some researchers believe that it is possible to peer deeper into the Earth's interior than the PLUME team is planning, by using more widely spaced instruments and applying various computational tricks to tease more information from the seismic data. In 1999, for instance, Harmen Bijwaard and Wim Spakman of Utrecht University in the Netherlands claimed to have imaged the plume beneath Iceland right down to the core–mantle boundary[1] — albeit at much lower resolution than the PLUME team hopes to achieve. But although many experts agree that Bijwaard and Spakman's results support the idea that there is a deep plume beneath Iceland, the method pushes the data to their limits, and the case is far from closed.

PLUME will help to clarify the picture — and it might be possible to obtain deeper images by placing PLUME's seismometers farther away from the Hawaiian Islands. "But we then would lose the ability to see the small details that allow us to determine where the plume is," says Laske, who believes that the configuration planned for PLUME offers the optimal trade-off — given the current number of seismometers available — between image depth and resolution.

Dynamic drive

As the PLUME team gears up for its deployment, a broader group of researchers is coming together to follow the trail that Laske and her colleagues are blazing. Last September, they held a workshop in Snowbird, Utah, to prioritize projects under the NSF's Oceanic Mantle Dynamics Science Plan. Conceived in 2000, this is a blueprint for interdisciplinary studies of the deep geological structures under the world's oceans. Devising a method to produce high-resolution seismic images of plumes in the lower mantle, all the way down to the core–mantle boundary, is one of its goals.

The plan has yet to be funded, but its prospects will receive a significant boost should PLUME produce the impressive results that its proponents anticipate. Once PLUME is over, its instruments will be added to the NSF's



Depth charge: a conduit of hot buoyant rock rises up from beneath the Hawaiian Islands to form an undersea plateau, or swell. As the lithosphere has moved across this hotspot, molten rock has occasionally broken through the surface to form volcanic islands. Researchers now aim to investigate whether the source of the plume lies in the upper mantle or whether it cuts right through the mantle from the boundary with the core (right).

pool of equipment for undersea seismology — the availability of which is the main constraint on the field's development. "With new technologies, we can do experiments that were not possible before," says John Orcutt, a geophysicist at Scripps and a principal investigator for PLUME. "But they tie up instrumentation for a long period of time."

Sink and swim

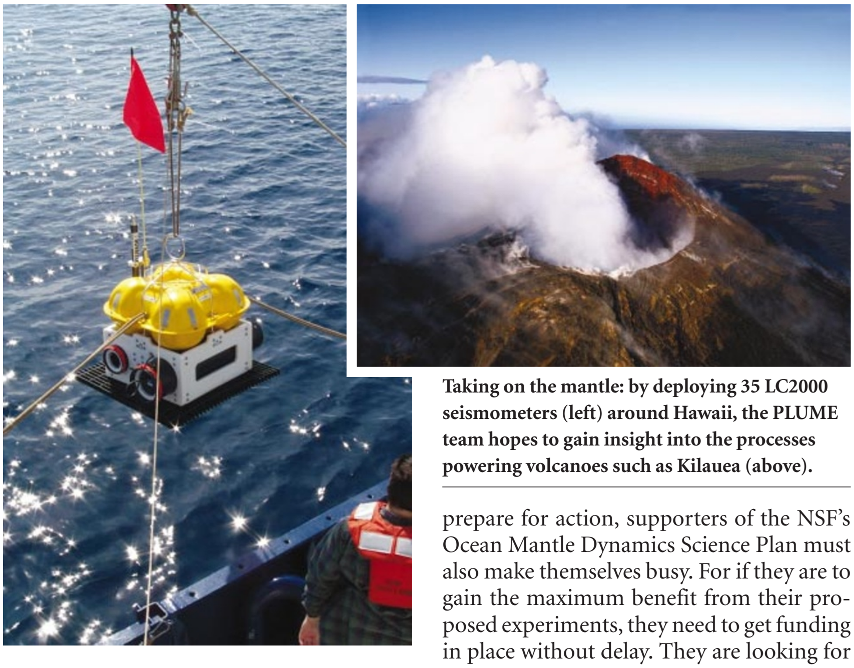
PLUME has been made possible by durable seismometers that can be dropped to the ocean floor, record data from earthquakes over many months, and then float to the surface to be recovered for redeployment. Those to be used for PLUME were developed by Orcutt from inexpensive prototypes dubbed 'L-Cheapos'. The current versions are more sophisticated, and cost $25,000 each. For a while, researchers knew them as 'L-Expensivos'. But the Scripps team eventually decided that this moniker was too frivolous, and renamed them LC2000s.

Each LC2000 is mounted on a concrete base that sinks it to the ocean floor. The base is all that is left behind after an acoustic signal prompts the equipment to ascend for retrieval. The current devices' improved robustness, along with technological advances in data storage and battery power, mean that they can be used for successive extended deployments.

The LC2000s can also record seismic waves with longer periods than was possible with the seismometers borne by the earlier L-Cheapos, which were blind to waves with periods longer than 45 seconds. Previously, researchers used differential pressure gauges to detect long-period waves, but these instruments don't record the direction from which the waves have come. The LC2000s should overcome this obstacle for waves with periods as long as 80 seconds. "This is the first time these will be deployed," says Laske. "They are very promising."

In 1998, some members of the PLUME team conducted a proof-of-principle experiment called Seismic Wave Exploration of the Lower Lithosphere, or SWELL. Led by Laske, Orcutt and Jason Phipps Morgan, now at GEOMAR, the Research Center for Marine Geosciences in Kiel, Germany, SWELL involved eight L-Cheapo seismometers placed 200 km apart in a hexagonal array around part of the Hawaiian swell. The data obtained revealed the western edge of the plume beneath the swell, and showed that it comes from a depth of at least 200 km (ref. 2). "SWELL showed it was technically feasible to do this type of experiment under the ocean," says Laske.

But PLUME is not just about seismology. As Laske and her colleagues chart the conduit of rising hot rock under Hawaii, geochemists on the team will be considering the plume's relationship with the atmosphere and oceans. For instance, studies of volcanic gas trapped in bubbles in rock at volcanoes on the Hawaiian islands, and dissolved in water from hydrothermal vents on the Loihi seamount, have shown that the ratio of the isotope helium-3 to helium-4 is much higher — 30 times at Mauna Loa on the Big Island, and 20 times at Loihi — than in the atmosphere[3]. It is also higher than in the gas dissolved in water from hydrothermal vents at the mid-ocean ridge, which is thought to come from the uppermost region of the mantle.



Taking on the mantle: by deploying 35 LC2000 seismometers (left) around Hawaii, the PLUME team hopes to gain insight into the processes powering volcanoes such as Kilauea (above).

J. BABCOCK
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It's a gas

Geochemists theorize that these elevated ratios show that the plume is bringing up rock from deep within the mantle that previously could not emit its helium-3. But proof awaits confirmation of the depths to which the plume extends, and more detailed geochemical analyses. "PLUME will give us clues to the way the Earth emits gas," says David Hilton, a geochemist at Scripps. And because the evolution of our atmosphere and oceans has depended heavily on gases emitted from the solid Earth, such clues are fundamental to understanding our planet's history.

Erik Hauri of the Carnegie Institution of Washington, who is leading the geochemical component of PLUME, hopes to deepen our knowledge by examining three major volcanoes on the Big Island of Hawaii: Mauna Loa, Kilauea and Mauna Kea. They are all within 60 km of one other, yet the composition of their lava is subtly different[4]. "I want to try to define what parts of the plume are giving rise to what volcanoes," says Hauri. This, in turn, should help seismologists to understand the labyrinth of conduits that may rise up to the surface from the plume's head.

While PLUME's principal investigators prepare for action, supporters of the NSF's Ocean Mantle Dynamics Science Plan must also make themselves busy. For if they are to gain the maximum benefit from their proposed experiments, they need to get funding in place without delay. They are looking for some $20 million to build 350 ocean-floor seismometers, plus running costs of about $10 million a year.

At the Snowbird workshop, participants decided that a top priority was to complete a seismic analysis of the United States' continental shelves out to at least 600 km along the west, east and gulf coasts. And they agreed that this will be most informative if conducted in parallel to a project called the USArray, in which portable seismometers will be deployed across the United States over the next decade, to image structures deep beneath the continent[5]. "You want to record the same earthquakes," Laske explains.

The USArray is scheduled to begin deployment in Southern California in 2005. The ocean mantle team would like to have its seismometers offshore by 2006. "It's going to be difficult," says Robert Detrick, a seismologist at the Woods Hole Oceanographic Institution in Massachusetts. "But if we really want to take advantage of the USArray timing, we should do it then."

Enthusiasts for marine seismology believe that their nascent field is poised to mine a rich vein of discoveries. "The plan is to look much deeper into the Earth," says Orcutt. "A lot of us feel the need to get on with it." Members of the PLUME team, meanwhile, hope that their project will provide an exciting preview of what is to come. "We've wanted to do an experiment like this for 20 years," says Hauri. "It'll be pretty cool." ■

Rex Dalton is *Nature*'s US West Coast correspondent.

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