Physics and Chemistry of Mantle Plumes

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Hot spot volcanic chains are a fundamental feature of the Earth's crust, but their origins are still poorly understood [*Okal and Batiza*, 1987]. The Hawaiian-Emperor volcanic chain, which dominates the topography of the central Pacific ocean floor, is the best developed and most intensely studied of the known hot spot tracks. It continues to be one of the world's most important field laboratories for the study of igneous processes, plate movements, mantle convection, structure, geochemical evolution, and the properties of the lithosphere.

Despite continued effort, fundamental questions regarding the composition, structure, and evolution of Hawaiian volcanos and their magma sources remain unanswered. This is largely due to the fact that only lavas representing the late stages in the evolution of the volcanos can be sampled at the surface. Most of the internal structure of the volcanos and evidence of their growth history and geochemical evolution are hidden from view. The most deeply eroded volcanos are exposed only to depths of a kilometer or so, whereas the volcanos rise some 5–15 km above the old ocean floor [*Moore*, 1987].

In late 1986, in recognition of the scientific value of observing the deep interiors of Hawaiian volcanos, a group of Earth scientists submitted a proposal to the NSF-sponsored drilling consortium DOSECC (Deep Observation and Sampling of the Earth's Continental Crust) to drill and core a volcano to retrieve and study a more complete stratigraphic sequence of its lavas. Following the reorganization of the drilling programs, this proposal was submitted to the Continental Lithosphere Program of the National Science Foundation in 1988 and again in 1989.

The proposed Hawaiian Scientific Drilling Project (HSDP) is aimed primarily at improving understanding of the structure and dynamics of the mantle, particularly with regard to the origin of mantle plumes and their interaction with the lithosphere and shallow asthenosphere. The proposed studies would also provide unique data on the physics and chemistry of magma generation, the internal structure of oceanic volcanos, and a number of other geophysical and geochemical problems. Drill coring is an effective means of addressing these problems because the targets—the lava accumulations of the large Hawaiian shield volcanos—are nearly horizontal subsurface features. The information accessible through drilling is unlikely to become available otherwise; hence it appears necessary to employ drilling to effectively address the scientific problems.

This article describes the primary scientific basis for the proposed project—elucidation of the physics and chemistry of the Hawaiian mantle plume on the time scale of a single volcano (about 10^6 years).

Origin and Chemistry of Mantle Plumes

The plate tectonic revolution and the concurrent exploration of other solar system bodies caused a profound change in the way Earth evolution and structure are viewed. In many ways, the shifts in the basic paradigms revolve around the central theme that convection in the Earth's interior is probably the single most important process determining the evolution of the Earth. Study of plate tectonics led to the realization that large-scale movements are taking place in the Earth's mantle, which brought into focus the need to understand the properties of mantle materials, convection itself, and the relation of mantle dynamics to seismic structure, the geopotential fields, the figure of the Earth, and the evolution of continents.

Since direct study of the mantle is in most cases impossible, indirect means must be employed. Such means include global heat flow studies, studies of the geoid, and seismic studies combined with high-pressure material properties research. These approaches study the mantle as it is currently. Geochemical studies of mantle-derived materials have a special role in that they provide insight both about the existing structure and composition as well as time-dependent information, such as residence times and dispersal times. The time dimension is accessible through the study of isotopic variations, and the most useful vehicles are basaltic lavas that bring the information to the Earth's surface from source regions in the mantle.

Over the past 2 decades, isotopic studies of oceanic basalts have shown that the mantle contains diverse materials [e.g., *Zindler and Hart*, 1986]. Convection should eventually make heterogeneities disappear, so their existence is a measure of the balance between the creation of heterogeneities and the efficiency of convection in homogenizing the mantle on different scales [*Richter et al.*, 1982; *Hoffman and McKenzie*, 1985]. One explanation for the persistence of heterogeneities is that they are continuously forming, so there is always a steady-state concentration of them in the mantle. Identifiable mechanisms for the introduction of heterogeneities include subduction of oceanic crust, including sediment derived from continents, subduction of continental lithosphere, and creation of "depleted zones" in the mantle in regions from which magma has recently been extracted. An alternative view is that large parts of the mantle are permanently separated from each other, the prevailing model being that the mantle is chemically layered. At one time, these models were considered in opposition to one another [*Zindler et al.*, 1982], but they have since been recognized to be complementary [*Zindler et al.*, 1984].

Within this general framework, the question of the nature of hot spots plays a central role. A common line of argument follows from the observation that hot spots seem to be fixed, or at least slowly moving in rela-

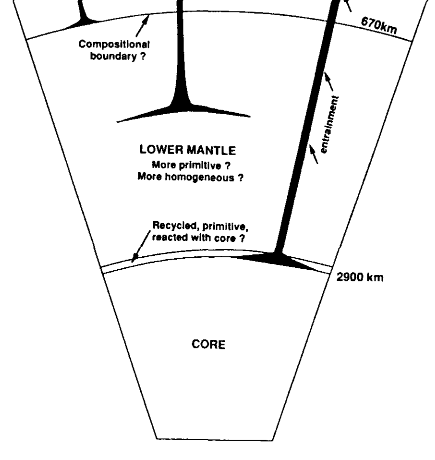

Fig. 1. Earth models and their association with the issues of the sources and dynamics of mantle plumes. The upper mantle is known to be depleted in magmaphile and volatile elements and to be very heterogeneous. The lower mantle may be more primitive (less depleted) and less heterogeneous. The lowermost mantle might contain primitive material, mantle material that has reacted with the core, or subducted slab (recycled) material. The 670-km seismic discontinuity may be a thermal boundary layer between two convecting systems, or simply a phase-change boundary. Plumes might originate at thermal boundary layers at (a) the 670-km level, (b) the core-mantle boundary, or (c) within the lower mantle. The erupted lava compositions are affected not only by the source of the plume, but also by the amount of entrainment (in upper and lower mantle) and the amount of assimilation of lithosphere.

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tion to the plates, suggesting a deep source [*Morgan*, 1971]. In addition, some of the geochemical properties of lavas associated with hot spots suggest that the mantle material from which they are derived is different and more primitive (that is, more similar to the original bulk composition of the Earth) than what is typical of the upper mantle as indicated by MORB (mid-ocean ridge basalts) [e.g., *Schilling*, 1973; *Chen and Frey*, 1985]. This mantle material is also different in such a way that it may not be explainable in terms of recycled oceanic or continental crust [*Kurz et al.*, 1982; *Hofmann and White*, 1982]. There has followed the hypothesis that hot spots represent "plumes" of chemically and isotopically special material from deep in the mantle.

If plumes are chemically and isotopically different from normal upper mantle material, the easiest explanation is large-scale layering, with inhibited exchange of material by convection between the layers (see Figure 1). The question of layering or otherwise isolated reservoirs is one of the fundamental questions about the Earth. The issue has many ramifications. For example, layered convection tends to aid the Earth in retaining heat in comparison to whole mantle convection [*Spohn and Schubert*, 1982]. Thus an understanding of the thermal history of the Earth hinges on this question, as does our ability to extrapolate our knowledge of the current style of tectonics to the Earth's early history.

Layering of the mantle is only possible if the chemical differences of the layers are such as to make the lower layers more dense [e.g., *Richter and McKenzie*, 1981]. Our understanding of the composition of the Earth, and thus of its origin, and the interpretation of seismic velocities in the deep Earth, are thus affected. If the lower parts of the mantle are not well degassed, it impacts theories of the origin of the atmosphere and oceans [e.g., *Hart et al.*, 1979]. If only the upper mantle has been involved in the formation of the continents, it affects the way we view the composition of the continents and oceans and how their compositions have changed with time [*DePaolo*, 1980].

The interiors of Hawaiian volcanos may carry particularly diagnostic information for assessing the ultimate origin and nature of mantle plumes. This statement stems from the observation that erosion exposes lavas that represent only the end stages of the volcanos' lifetime, and that there are trends in composition in these late-stage lavas that suggest that the interiors of the volcanos are different. Even in the most deeply eroded volcanos, only about 10–15% of the history of a volcano can be observed. The end stages of most volcanos involve a transition from tholeiitic lavas to alkalic lavas. The long-standing model is that all the lavas from the inception of the volcano to the transition stage are tholeiitic [*MacDonald and Katsura*, 1964], but there are few direct observations to support this. Recent observations at Loihi [*Moore et al.*, 1982] and in the submarine part of the Kilauea East Rift Zone in fact suggest that alkali basalt may be common throughout the lifetime of a volcano.

A trend discovered by *Chen and Frey* [1985] suggests that the interiors of some of the volcanos contain flows with geochemical signatures different from the exposed flows. Figure 2a shows the Nd and Sr isotopic compositions of Haleakala basalts. Among these basalts there is a trend from posterosional alkalic lavas to the late-main-stage alkalic lavas, and then to transitional tholeiitic lavas, in the sense that the isotopic compositions look less like those of MORB and more like those of primitive mantle material ($\epsilon_{Nd} = 0$). This has been interpreted as evidence for two major mantle sources for the lavas. One source, the one with the MORB-like signature, is interpreted to be the oceanic lithosphere. The other source is presumably a deeply-sourced mantle plume. There is a suggestion that farther down in the lava sequence, in the "middle" of the main "tholeiitic" stage, the lavas may have isotopic compositions that are different from the MORB-type values. It is noteworthy that the study of *Chen and Frey* [1985], which was an important advance from previous work, was done on drill-core material.

Two other observations are important. Hawaiian lavas, including those from Loihi seamount, have very high $^3He/^4He$ ratios [*Lupton and Craig*, 1975; *Kurz et al.*, 1982; *Staudigel et al.*, 1984], which indicate that the magmas come from mantle reservoirs that are more primitive than the MORB reservoir (Figure 2). Because of differences in concentrations in different reservoirs, the primitive He may be relatively less diluted by upper mantle material than are Nd and Sr. In addition, in the case of one eroded Hawaiian volcano, the Koolau shield of Oahu, there is a strong indication of the presence of mantle material of substantially different composition (Figure 2a). The Koolau basalts also have Hf and Pb isotopic compositions that could be considered to be primitive [*Stille et al.*, 1983]. The basalts of Oahu show a relationship similar to that of the Haleakala lavas in that the posterosional lavas (Honolulu series) have isotopic compositions approaching those of MORB, whereas

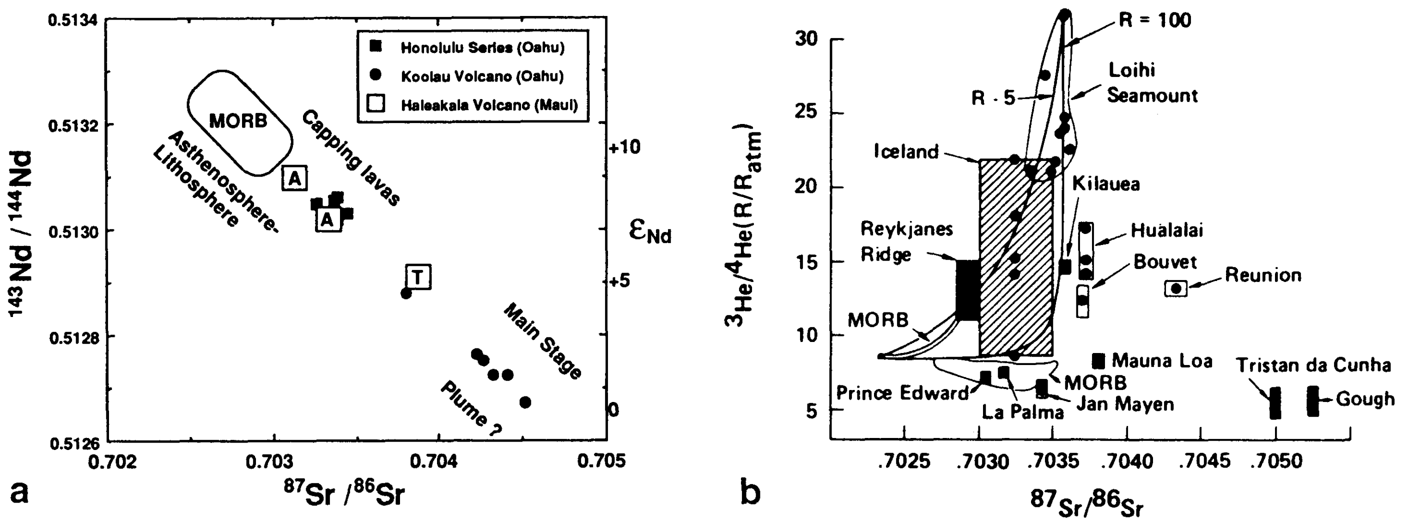

Fig. 2. (a) Nd and Sr isotopic ratios in lavas from Oahu and the Haleakala volcano of Maui (data from Roden et al. *[1984] and* Chen and Frey *[1985]). Tholeiities (T and solid circles), erupted earlier, are much more voluminous, and have isotopic ratios more like whole Earth values ($\epsilon_{Nd} = 0$) than those of alkali basalts (A) erupted near the end of the main stage of shield building, or nephelinites (solid squares), which were erupted well after the cessation of shield building. These data have been interpreted in terms of increasing lithospheric (or local asthenospheric) contributions to the magmas in the waning stages of the volcano's lifetime. The main stage is generally hidden from view beneath the late-capping lavas. (b) He and Sr isotopic ratios of some oceanic basalts, showing that active Hawaiian volcanos contain He that is rich in ^3He, which distinguishes them from mid-ocean ridge basalt and many other oceanic basalts.*

the older tholeiites of the Koolau volcano have isotopic compositions far removed from those of MORB.

Of the known hot spots and hot spot tracks, Hawaii is the obvious place to attempt to further elucidate the nature of hot spots. Continental localities are more complicated because of the potential for contamination of the lavas by continental lithosphere. Mid-ocean ridge localities can be eliminated because upwelling at the ridges tends to dilute the plume signal. Of the remaining ones, Hawaii is a much longer-lived feature, much more is known about it, and it is still active.

Magma Genesis and Plume-Lithosphere Interactions

Since the importance of the relative fixity of hot spot volcanism was realized, several mechanisms have been proposed to explain it. The most widely recognized of these is the mantle "plume" hypothesis [e.g., *Morgan*, 1971]. Other models include one of a propagating crack in the lithosphere [*Jackson and Wright*, 1970], shear melting with thermal feedback [*Shaw*, 1973], and diapiric upwelling along a line of structural weakness [*McDougall*, 1971]. Some of these models are applicable to mid-plate hot spots, but would be unlikely to explain hot spots that occur at mid-ocean ridges. The plume hypothesis has also been considered as a mechanism for generating continental rifting.

According to the "plume" hypothesis, mantle material rises diapirically from an approximately fixed location deep in the mantle. As it nears the surface, the rising mantle material begins to melt in response to decreasing pressure, and the liquid portion escapes upward and erupts on the growing volcano. Although the source of rising diapirs is fixed, the oceanic lithosphere is moving continuously. As a result, a linear series of volcanos develops; active volcanism is limited to the region that currently overlies the fixed plume of rising mantle material, but a sequence of inactive, progressively older volcanic edifices that grew when they previously sat astride the plume extends away from the site of active volcanism in the direction of plate movement. In the case of the Hawaiian-Emperor volcanic chain sitting on the northwestward moving Pacific plate, active volcanism is restricted to the southeastern end of the chain, where there has been a source of magma for about 70 m.y.

Recent work has refined the plume model. Laboratory and theoretical models suggest that plumes originate from thermal/chemical boundary layers in the mantle or at the core-mantle boundary and consist of a large-diameter "head" and a "tail" with a much smaller diameter [*Whitehead and Luther*, 1975; *Richards et al.*, 1989]. When the head reaches the melting zone at shallow depth in the mantle it produces a huge, rapid outpouring of lava. Continental flood basalt provinces are candidates for plume head-related volcanism [*Richards et al.*, 1989]. The plume head is predicted to entrain large amounts of material external to the plume and thus represents a complex magma source geochemically. The column represented by the plume "tail" is expected to be a long-lived feature; a conduit through which hot, bouyant material from the deep boundary layer "drains" to the near-surface region of the mantle.

This model presents a relatively simple framework for understanding the nature of magma sources in an active plume long after initiation, which is the case applicable to Hawaii. The structure proposed resembles that suggested by *Schilling* [1973] for the Iceland plume. This model raises several questions. For example, how well does the plume material arriving at the base of the lithosphere mix with the surrounding lithospheric and sublithospheric mantle? How is such mixing related to magma generation rates and magma types? Is the flow in the plume conduit steady or are there variations with time? With regard to the last question, it has also been suggested that plume flow may be in the form of a train of diapirs rather than a pipe [*Schilling and Noe-Nygaard*, 1974; *Olson and Singer*, 1985].

Models for the behavior of melt segregating from flowing, partially molten regions of the mantle are not yet well enough developed to predict the details of the melting-mixing-segregation processes at the plume-lithosphere conjunction [cf. *Ribe and Smooke*, 1987; *Richter*, 1986; *McKenzie and Bickel*, 1988]. However, the geochemical-petrological time series that could be generated from a continuous sampling of the volcanic output of a volcano over most of its lifetime could be one of the best approaches available for obtaining a phenomenological basis for understanding these aspects of the physics of hot spots. Modern methods of trace element analysis, coupled with existing models for melt segregation, allow us to invert trace element compositions to determine parameters associated with the melting process such as the melt fraction attained and the depth of melting [*Feigenson and Spera*, 1981]. These parameters can only be obtained if one knows that the composition of the magma source is unchanging with time and/or position. To constrain this, one must bring in isotope ratios, which can identify the roles of different magma sources. In Hawaii we have a special situation where we know already that there are two magma sources involved—plume and lithosphere/asthenosphere—and that they have distinct isotopic signatures. The Hawaiian hot spot thus represents a rich natural laboratory for the study of fundamental planetary processes.

Summary

The goal of the Hawaii Scientific drilling project is to obtain a continuous sequence of lavas from a single Hawaiian volcano extending from post-shield alkalic lavas back in time to the early stages of the volcano's growth, and to produce from these samples an essentially continuous chemical and isotopic record of the lava output. This time series would provide a unique opportunity for determining (1) the nature of the mantle sources of the magmas (for example, upper versus lower mantle; plume versus lithosphere/asthenosphere) and how they change with time; (2) the nature and temporal evolution of the melting and magma segregation processes in the mantle; and (3) the roles of shallow versus deep magmatic processes in the generation of the lavas erupted at the surface. With good age control, the rates of magma generation, changes in magma source characteristics, and the role of shallow magmatic processes can be determined, providing a unique characterization of hot spot magmatism.

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House Panel "Terminates" *Freedom*

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The House appropriations subcommittee with responsibility for the National Aeronautics and Space Administration terminated funding for Space Station *Freedom* on May 15. The surprise action by the VA, HUD, and Independent Agencies subcommittee, chaired by Bob Traxler (D-Mich.), threatens a favorite space project of the Bush administration, and calls into question the generally strong support for the space station believed to exist in Congress.

Traxler cited budget constraints to justify the act. The funding cut-off, he said, "reflects the fact that our federal government's budgeting has hit a dead end. We simply can no longer afford huge new projects, with huge pricetags, while trying to maintain services that the American public expect to be provided."

In terminating *Freedom,* Traxler added, the subcommittee was "able to provide nearly full funding for other space science research efforts, and we have provided full funding for the research and education programs of the National Science Foundation." Other sources, however, indicate that the subcommittee deleted the funding for the NSF's Laser Interferometer Gravitational Observatory (LIGO), freeing up money to increase other NSF programs beyond the administration's request.

"'This is a very serious blow'" to the space station, Robert S. Walker (R-Pa.) was quoted as saying in the May 16 *Washington Post*. "Walker said it would be 'very hard' to reverse the decision and would 'take major pressure from the [Bush] administration.'"

The subcommittee released figures that compared its cuts to NASA's budget request with and without *Freedom*. By retaining the space station, the subcommittee would have made a "general reduction" of $35 million in NASA's space science and applications area. Also, the Earth Observing System would have been cut by $75 million, CRAF-Cassini by $45 million, and the Advanced X-Ray Astrophysics Facility by $50 million. With *Freedom* removed, however, the original budget requests for EOS, CRAF, and AXAF survived intact. The savings from deleting *Freedom* will also fund veterans' and environmental programs and other social services.

The subcommittee's "marked up" appropriations bill, as its adjustments to the president's budget request are called, is not the final word on the space station. The bill must now be approved by the full House appropriations committee. On the Senate side, the appropriations subcommittee chaired by Barbara Mikulski (D-Md.) has not yet made its own recommendations on a parallel bill.—*Lynn Teo Simarski*

Senate Handles NASA Gently—So Far

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"When we ask these tough questions today, know that they're so we can really argue the case of NASA," Senator Barbara Mikulski (D-Md.) told Richard Truly, administrator of the National Aeronautics and Space Administration, on May 8 as she opened a succinct and generally friendly hearing on NASA's budget. The gentle tone of Mikulski and most of the subcommittee on VA, HUD, and Independent Agencies that she chairs was in striking contrast to the contentious reception Truly and Space Station *Freedom* got the previous week from a House committee.

Evidently prepared for another possible confrontation, the NASA head brought along enough of his top staff to fill the first two rows of the hearing room, but he faced mostly supportive senators. Mikulski pledged to be "a very strong advocate for the NASA core." Ranking minority member Jake Garn (R-Utah) was also positive about NASA, while calling upon President Bush to lobby personally for his generous NASA request.

"The most serious issue NASA faces in this climate of tight budget is the future of the space station," Mikulski said. The General Accounting Office's recent study of *Freedom*, which charged NASA with underestimating the station's cost up to 1999 by $10 billion, came in for some hard knocks at the hearing. (AGU also recently appeared before Congress to challenge NASA's estimate for *Freedom*'s cost; see *Eos*, May 7, 1991.) Both Garn and Phil Gramm (R-Tex.) bluntly disparaged GAO's credibility. GAO is "increasingly unscientific," Gramm charged.

Truly defended NASA's cost estimate for the space station, once again pleading that the station be taken off the "funding seasaw" it has ridden the last few years. "Without the funding that's requested, this country is not going to see a space station," he said.

The lone dissonant voice raised at the hearing belonged to J. Robert Kerrey (D-Nebr.), who expressed concern about *Freedom*'s scientific usefulness. "I support the space station but it's a very tentative support," he said.

When Kerrey brought up NASA's science programs, Truly called them "the jewel in NASA's crown." When Kerrey asked whether or not NASA's space science programs were being "robbed" to fund other projects, Truly answered that this was "definitely a misperception." AGU and other scientific societies continue to remind Congress about the Augustine Committee's recommendation that science be NASA's first priority. Truly seemed to be responding to this when he said, "I believe that one of the worst mistakes that could be made with regard to the Augustine report is for each part of the space constituency to reach into the report and pull out their favorite sentence, their favorite program, and put that above all." At one point, Gramm said that the real issue regarding NASA is not science but "America's leadership in space."

The House and Senate budget resolution just passed on the floor of Congress suggested cutting NASA's budget by $1.2 billion. Mikulski asked whether the space station would still be worth funding if this cut were actually made. Truly implied that in such a case all NASA sectors would suffer, saying that "a cut that deep would put not just the space station for a 're-look' but also the space science programs" and others.

Rumors persist in Washington, however, that a large portion of the cut will affect either NASA's science programs or the space station, but not both.