Hotspot Volcanoes and Large Igneous Provinces

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Abstract

Ocean island volcanoes and large igneous provinces, both of which represent mantle plume volcanism, are attractive drilling targets because of compelling scientific issues, the layered structure of lava accumulations, and the demonstrated capability to retrieve a high percentage of core in many environments. Although the programs supporting on-land scientific drilling — ICDP, and in the U.S., NSF-Continental Dynamics — are nominally about continental drilling, the primary dichotomy is between on-land drilling and ship-based offshore drilling (IODP). Mantle plume volcanic rocks are accessible to on-land drilling in many oceanic settings as well as on continents. Drilling and coring ordered, datable sequences of lavas can address questions about the mechanisms of magma generation and transport, the geochemical and geophysical structure of mantle plumes and their relationship to the structure and composition of the deep mantle, the structural evolution of large volcanoes, the subsidence history of volcanic piles, the flexural properties of the lithosphere, and the hydrology, alteration history and geobiology of subsurface volcanic environments.

1 Introduction

Hotspot, or mantle plume, volcanism is one of the major processes affecting the interior of the Earth. Mantle plumes may be the primary mechanism of heat loss for the Earth's core and are also one of the primary driving factors in plate movements. Plume heads are influential in forming and modifying plate boundaries, while plume tails and their surface tracks constitute major features of the Earth's lithosphere (e.g., Richards et al. 1989;

Duncan 1991). The influence of mantle plumes, and the large lava accumulations that are associated with them, on continent formation and evolution constitutes a continuing theme of the science of continental dynamics (e.g., Hill et al. 1992).

Non-hotspot related volcanism on the Earth is produced in conjunction with plate tectonic processes. Examples are the new oceanic crust formed at mid-ocean ridges, the linear volcanic chains associated with subduction zones, and the relatively small volumes of lava associated with continental extension (Fig. 1). The magma supply for non-hotspot volcanoes is thought to come from melting of the uppermost mantle, so the geochemistry and petrology of non-hotspot lavas tell us mainly about the composition of the upper mantle and processes that occur there. One great attraction of mantle plume volcanoes, from a petrological and geochemical standpoint, is that the mantle plume that produces them may have originated in the lower mantle, most models suggesting that the strongest plumes originate from near the core-mantle boundary (Morgan 1971, Christensen 1984; Hansen and Yuen 1988; Van Keken 1997; Jellinek and Manga 2002). Mantle plumes are consequently messengers from the deepest levels of the silicate part of the Earth (DePaolo and Manga 2003; Brandon et al. 1998). Mechanisms leading to volcanism on other planets in the solar system, such as Mars and Venus, are believed to closely resemble the processes responsible for terrestrial hotspot volcanism (Kiefer and Hager 1991).

Although the programs supporting on-land scientific drilling — ICDP, and in the U.S., NSF’s Continental Dynamics — are nominally about continental drilling, the primary dichotomy in terms of drilling technology and logistics is between on-land and ship-based offshore drilling (IODP). Hence drilling in both continental large igneous provinces (LIPs) and in oceanic hotspot islands has come under the auspices of the continental drilling programs. The reasons for drilling oceanic islands and LIPs revolve around scientific issues in geochemistry, petrology, volcanology, geodynamics, biology, and hydrology. The research questions in mantle geochemistry, petrology and volcanology have been the primary impetus, but unanticipated results relating to biology, hydrology and geodynamics have come from the drilling that has been already carried out; for example, in Hawaii (DePaolo et al. 1996, 2001b; Stolper et al. 1996).

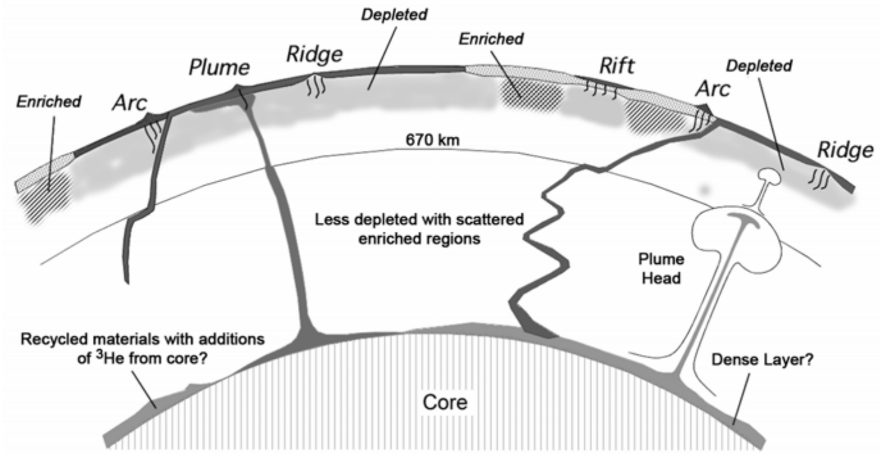

Fig. 1. Schematic cross section of the Earth's mantle, core and crust showing the spatial distribution of various mantle reservoirs with specific element and isotopic geochemistry. Depleted and enriched designation refers to incompatible trace elements with reference to an idealized "bulk mantle" composition. Most types of volcanism (mid-ocean ridge, island arc, continental margin arc, and continental rift) involve melting of the uppermost upper mantle. Hot spot volcanism, especially for the larger plumes, such as Hawaii and Iceland, may be the only case where the melting involves mantle that has recently ascended from much deeper in the Earth. The sources of plumes are shown here as being near the core-mantle boundary, or from a large plume head in the mid-mantle. There is current debate about whether plumes come from the core-mantle boundary region, and if they do, whether they come from the core-mantle boundary itself, or from just above an intrinsically dense layer mantling the core. There is also debate about whether the mantle at the core-mantle boundary is a primordial layer that is billions of years old, or composed of recycled oceanic lithosphere that has been exposed to the ocean and atmosphere relatively recently.

An important characteristic of ocean islands and LIPs makes them attractive for drilling: the volcanic accumulations are made of subhorizontally stacked lava and pyroclastic sequences, some as much as 5 to 10 km in thickness, all arranged in chronological order. Drilling intersects the primary structure at a high angle and hence a maximum amount of information can be gained through drilling. Experience from the Hawaii Scientific Drilling Project (HSDP) shows that subaerial lava sequences can generally be cored efficiently, with penetration rates of 25 to 40 m/day. Submarine hyaloclastite is also easy drilling. Submarine lavas are more difficult to drill because the fractured pillows result in slow penetration rates (5–15 m/day) and hole stability problems. HSDP has also shown that it is possible to choose drill sites where few intrusive rocks are encountered, long stratigraphically-continuous sequences can be cored, and both the lavas and pyroclastic rocks are unaltered by post-eruption processes. The clearest justification for drilling volcanic sequences exists for young lavas from active or recently active volcanoes where the magmatism can be studied in the geodynamic context in which it was generated. Young volcanic sequences are also least subject to dissection by erosion, and thus only drilling can access the deeper levels of the lava piles. A major challenge for studying young basalt lavas is obtaining precise ages for the lavas (geochronology), but in higher-K lavas this may be less of a problem (e.g., Sharp et al. 1996, 2005).

2 Hotspots: Mantle Chemistry to Lithosphere Dynamics

2.1 Mantle Geochemistry

Models for the structure of the mantle continue to evolve but are not easily testable (Fig. 1; cf. Zindler and Hart 1986; Hofmann and White 1982; Hofmann 2003). Particular interest is now focused on the core-mantle boundary region and the lowermost mantle. If mantle plumes sample this area, then detailed studies of plume-related volcanic rocks are one of the few ways to characterize the geochemistry of the deepest mantle. The mantle plume model for hotspot volcanoes has recently come under attack (Foulger et al. 2002), but is still the best explanation for quasi-stationary intense volcanism far from plate boundaries (Davaille 2003; DePaolo and Manga 2003), large volumes of oceanic plateaus and large igneous provinces (Richards et al. 1989), and the different geochemical characteristics of OIBs and MORBs (e.g., Hofmann 2003). The objective for the future is to better characterize the internal geochemical and petrological structure of plumes to get more information about the deepest parts of the mantle (Bryce et al. 2005). Systematic drilling on ocean island hot spots and in LIPs may be the only way to get the necessary information.

Large igneous provinces are thought to result when a new plume, originally generated at the core-mantle boundary, arrives under the lithosphere and begins to melt (Griffiths and Campbell 1990). The explanation for the large amount of lava (ca. 10^6 km^3) erupted in a short time (about 10^6 yr) is that a large volume of anomalously hot mantle enters the depth range where melting can occur (from about 80 to 180 km) in a short time. An essential result of the numerical models of mantle plumes (Farnetani et al. 2002) is that the part of the plume that melts to produce lava comes almost exclusively from the very bottom of the mantle — within 25 to 50 km of the basal compositional boundary — which can be either the surface of the outer core or the top of a dense silicate layer mantling the core. The volcanic rocks produced therefore represent the only sampling that is possible of this critical boundary layer in the Earth. Answers to questions such as the degree to which the core and mantle are in chemical communication (Jeanloz 1993; Brandon et al. 1998), whether the base of the mantle is a graveyard for subducted slabs (Hofmann and White 1982), and even questions such as when the core formed and the age of the Earth relative to meteorites (see Boyet and Carlson 2005) may be locked in the lavas of hotspots and LIPs.

A more detailed schematic of plume melting and magma transport under Hawaii and other long-lived oceanic hotspots associated with plume “tails” is shown diagrammatically in Fig. 2. Much like in the models of Farnetani et al. (2002), the only part of the plume that melts is the hot central core, and this plume material must come from a thermal boundary layer at or near the base of the mantle. Hawaiian volcanoes, however, because they sit on a moving oceanic plate, systematically sample across the melting area of the plume as they grow. In the 1 to 1.5 million years it takes them to grow, a volcano drifts about 100 to 150 km across the plume and hence samples first one side, then the middle, and then the other side of the melting region. This “scan” of the plume top provides information on the detailed structure of the lowermost 25-50 km of the mantle, all laid out in sequence in the lavas of individual volcanoes, and accessible only by drilling.

An example of the information that can be extracted from the systematic sampling associated with a continuous lava sequence is shown in Fig. 3. The ^{3}He/^{4}He ratio of the HSDP lavas increases systematically down core, and the ratios also become more variable (Kurz et al. 2004). The deeper lavas are also older, so the data succession down core is also an age progression, and, according to the model of Fig. 2, a “scan” over the plume. The results suggest that the central part of the plume has high ^{3}He/^{4}He, whereas the periphery of the plume has lower ^{3}He/^{4}He similar to mid-ocean ridge lavas. The high ^{3}He signal is interpreted to be associated with the base of the mantle. This characteristic is compatible with the basal layer of the mantle being primordial material but is not easily reconciled with the basal layer being recycled subducted oceanic crust. The narrowness of the ^{3}He signal suggests that it is confined to the central part of the melting region, which in turn is confined to the central part of the plume (Bryce et al. 2005). The ^{3}He-rich material must therefore come from within perhaps 10 km of the base of the mantle, which suggests that perhaps the ^{3}He is coming from the core. Figure 3b shows that the high-^{3}He lavas also have high ^{208}Pb, and together these characteristics are similar to lavas from the young submarine volcano Loihi, which must now be close to where magma derived from the core of the plume is reaching the surface.

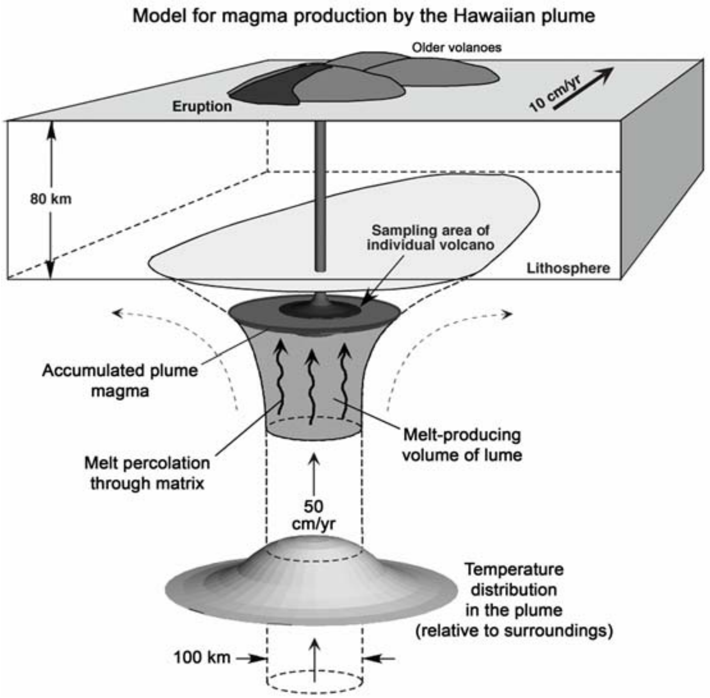

Fig. 2. A simplified model for magma production in the Hawaiian plume showing how a lava sequence can be related to the thermal and chemical structure of a plume. The Hawaiian volcanoes drift slowly over the melt-producing region of the plume during their 1 to 1.5 million-year active lifetimes. The magma supplied to an individual volcano probably comes from only a fraction of the area of the melt-producing region, so the volcano’s “sampling area” sweeps over the plume as the volcano grows. The melt, as it percolates upward within the melting volume of the plume, also samples vertical heterogeneity in the plume. Ordered sequences of lavas, such as those recovered by the Hawaii Scientific Drilling Project, represent a systematic sampling of the vertical and radial structure of the plume. For Hawaii, the part of the plume that is hot enough to melt is only the central core due to the thick lithosphere. In other hot spots, where the lithosphere is thinner, a larger fraction of the plume melts. Similar models may apply to flood basalts, and analyses of the lavas recovered from coring are a unique and systematic record of the melting processes and magma source structure.

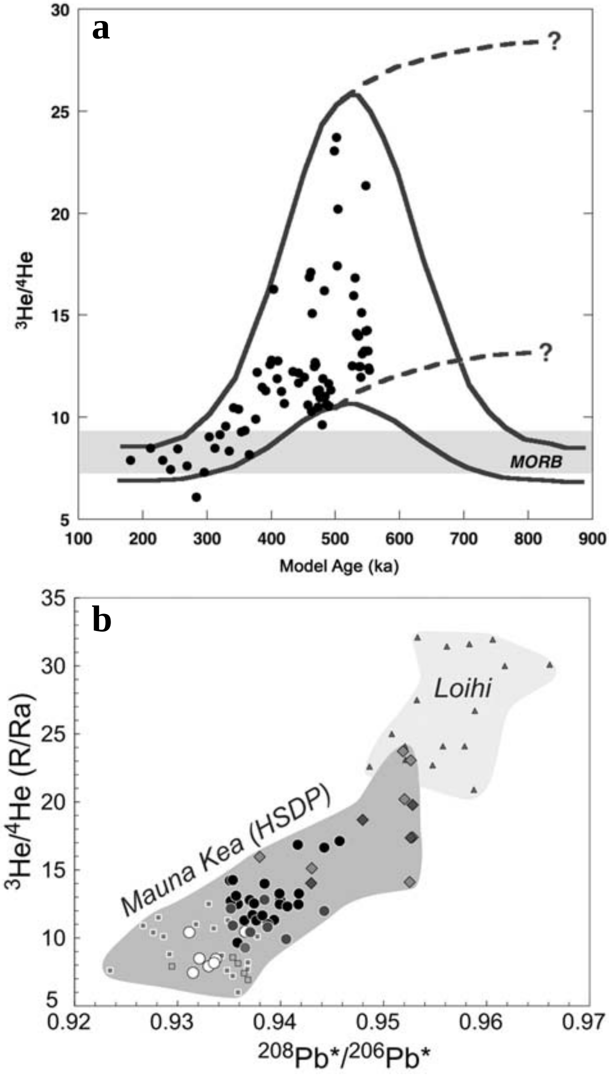

Fig. 3. a. Helium isotopic ratios measured in HSDP lavas versus age (Kurz et al. 2003). Age in this case comes from the model of DePaolo and Stolper (1996). There is a very large change in the helium isotopic character of the lavas through the HSDP section. The high $^3He/^4He$ ratios are associated with the Earth's deep mantle and may come from the core-mantle boundary region. One model here shows what would be expected for a radially-zoned plume; the other shows what an asymmetric plume might look like. **b.** Helium isotope ratios plotted against ^{208}Pb, showing that samples from the deepest levels of the HSDP2 core approach the isotopic compositions of lavas from Loihi (Eisele et al. 2003).

The Hawaii example is one of the simplest in terms of geodynamics. Models for many other hotspots (e.g., Galapagos, Azores, Tahiti) need to be more complex because the movement of the lithosphere relative to the plume has changed with time. Iceland is yet another example, where the plume comes up at a ridge so that much more of the plume melts and hence the lavas provide information on a thicker vertical section of the base of the mantle (Ito et al. 2003). Kerguelen is yet a different case, because initially the plume activity was associated with continental breakup and a ridge environment, and then it evolved into an intraplate environment, moving farther and farther from a ridge with time (e.g., Frey et al. 2000; Weis et al. 2002; Weis and Frey 2002).

2.2 Volcanology

The internal structure of large oceanic volcanoes is still a matter of considerable debate because little direct information is available. It is inferred that the volcanoes start out as steep-sided cones of pillow basalt on the ocean floor. Once they breach the ocean surface, they should evolve to a 3-layer structure, including subaerial lavas on top, a large apron of volcaniclastic material, and the pillow-lava seamount at the center. The thickness of each layer depends on seafloor depth and subsidence during volcano growth, and the presence or absence of volcanic rift zones. The proportion of intrusive rocks making up the interior of large volcanoes is also unknown but subject to much speculation (Walker 1990). The HSDP data confirm the 3-layer model (although less hyaloclastite was found than expected; Figs. 4 and 5), but indicate that some estimates of the amount of intrusive rock are far too high.

The growth rate of hot spot volcanoes is also important information. Geodynamic models that give the temperature and upward velocity as a function of position in the plume, combined with petrological models for mantle melting, yield estimates for the amount of magma produced in the plume per unit time. Magma production should be at maximum above the axis of the plume and drop off systematically with radial distance away from the plume axis (Watson and McKenzie 1988; Ribe and Christensen 1999; DePaolo and Stolper 1996). The overall eruption rate of the volcanoes is related to this magma production rate, but it is not certain what fraction of the produced magma is actually erupted and/or intruded into the volcanic edifice. The Ar-Ar dates obtained on the HSDP core (Fig. 6a) provide the first detailed picture of the growth history of a large oceanic volcano over an extended time interval. The measured ages can be accounted for roughly with a simple model for the magma production in the plume (DePaolo and Stolper 1996; Figure 6b), but these measures are far greater than had been estimated based on dating of surface outcrops and dredged submarine lavas (Moore and Clague 1992).

For Kerguelen, as a contrasting example, an overall 5 degree dip from west to east allows for sampling different lava compositions, from tholeiitic to alkaline as age decreases over many millions of years (Nicolaysen et al. 2000). The age and composition progression corresponds with changes in the type of magma source, which is analogous to Hawaii, but on a much longer time scale. The early stages of the building of the island on the Northern Kerguelen Plateau indicate influence from a depleted mid-ocean ridge-type reservoir, with the source of magmatism being along the southeast Indian Ridge (SEIR) (Weis and Frey 2002). Comparison of various oceanic settings with different compositions will lead to a better understanding of oceanic volcano structure.

2.3 Hydrology, Microbiology, and Alteration

The subsurface hydrology of oceanic islands is largely unknown, even though there have been simple, general models for a long time. One unexpected feature of the HSDP drill site is the low temperatures that extend to great depth (Fig. 7). The temperature profile requires that cold seawater (and/or deeply penetrating groundwater) be circulating through the volcanic pile, even at depths grater than 3 km (Thomas et al. 1996; Kontny et al. 2003). A unique feature of core from oceanic islands is that it allows for understanding both alteration of basalt glass and the activity of microorganisms as they develop progressively with time and temperature (Walton et al. 2004). Most other situations require study of samples with unknown temperature history, or do not preserve the stages of progressive alteration and infection that can be observed, for example, in the HSDP core. The alteration process may be significant in understanding the reactions and compositional exchange between seawater and basalt glass at low temperatures, providing an analogue system for the early history of fluids that circulate through mid-ocean hydrothermal systems and that lead to significant ore deposit formation. Evidence of traces of microbiota may help document the extent, abundance, and level of organic activity in the subsurface (Fig. 8).

Fig. 4. Examples of rock cored by the HSDP. The upper picture is a portion of a fresh aa flow interior. In the center is “hyaloclastite” or volcanic sediment, and lower is pillow basalt. At all levels of the HSDP core, fresh volcanic rocks were recovered.

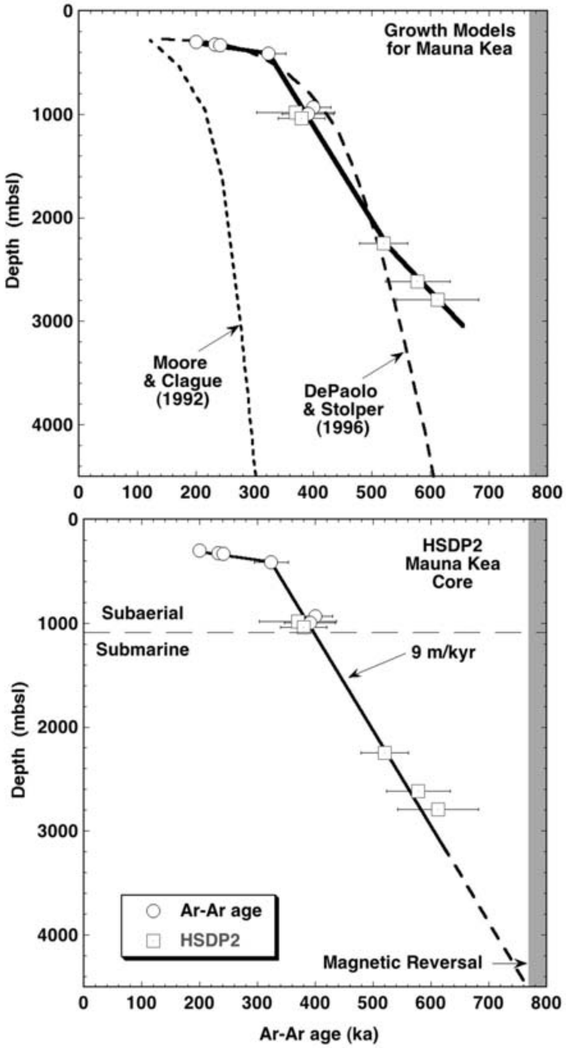

Fig. 5. Age versus depth for Mauna Kea lavas from the HSDP core. The age information is critical for reconstructing the position of Mauna Kea in the past relative to the hot spot, and allows the geochemical data to be related to three-dimensional structure in the plume. The data are also important because they show for the first time how long the volcanoes take to grow. Simple models for the volcano growth from plume magmatism (DePaolo and Stolper 1996) reproduce the observations only moderately well. The constant accumulation rate from 600 to 320 ka is not predicted, although the age data have sufficient uncertainty to allow for the predicted decreasing accumulation rate with time. Previous models published prior to drilling (e.g., Moore and Clague 1992) had suggested that Mauna Kea was only about half the age that it is.

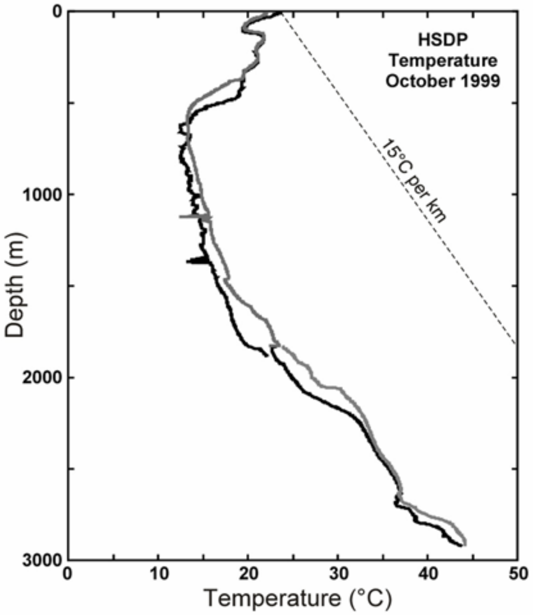

Fig. 6. Temperature versus depth in the HSDP well measured about 1 month after cessation of drilling in 1999. A geothermal gradient of 15°C per kilometer might be expected for a lithosphere of about 90 km thickness with a basal temperature of 1350°C. The observed temperatures are much lower, although a gradient close to the expected is present below about 2000 m depth. The anomalously low temperatures are believed to be due to rapid circulation of cold seawater through the basalt pile. Radiocarbon ages of saline water pumped from the well at about 800 m depth confirm the relatively rapid flow of a seawater-like fluid through the volcanic rocks (Thomas et al. 1996). In the upper 300 m of the well, the cooling is due to freshwater aquifers. The discovery by HSDP of significant fresh groundwater resources within the volcano is of considerable interest for water resources on all of the Hawaiian Islands.

2.4 Magmatic Processes

Ocean island volcanism constitutes a fertile test bed for models of the generation and transport of magma from the mantle. Even for the simplest models of axisymmetric plumes, there is considerable uncertainty about the depth and extent of melting, the role of water and mineralogical heterogeneity, the percolation of magma through the melting zone, and the transport of the magma to the volcano's shallow plumbing system. The growth rate of volcanoes gives information on the temperatures, upwelling velocities, and melt generation rates in the mantle (Ribe and Christensen

1999). The petrological and geochemical characteristics of the lavas tell us about depth of melting, extent of melting, residual minerals in the melting region, and crystallization processes in the magma en route to the surface. Isotopic characteristics help to constrain the source characteristics of the mantle plume, the contributions of various components, and the size and composition of heterogeneities.

Studies of Hawaii, Iceland, and other hotspot lavas continue to yield new insights into magma generation processes and their relation to geodynamic models, mantle composition and heterogeneity (e.g., Hauri 1996; Norman and Garcia 1999; Stolper et al. 2005; Kincaid and Hall 2005). The extended, ordered sequences of lavas that can be obtained by drilling are a unique resource for estimating the length and time scales of magmatic processes and source characteristics (DePaolo 1996; Eisele et al. 2003; Blichert-Toft et al. 2003; Haskins and Garcia 2004).

2.5 Lithosphere Dynamics

Although lithosphere flexure has been studied for decades, there is still a far from complete understanding of the effective thickness and rheology of oceanic lithosphere (Watts 2001). Flexure models are critical for understanding the subsurface volumes of oceanic volcanoes (Moore 1987), and hence the relationship between volcano volume and magma production in the mantle plume. Unique information on subsidence and flexure can be obtained while recovering lava samples for petrological analysis. In Hawaiian volcanoes, for example, the subaerial-submarine transition is typically within 1.5 km of the surface (e.g., Fig. 4), and thus is accessible by drilling through the subaerial lavas — the part of the lava section that can be cored most efficiently. The depth to the subaerial-submarine transition, combined with geochronological study of the lavas (Fig. 9), provides firm data for evaluation of lithosphere flexure models (Sharp et al. 1996; DePaolo et al. 2001a). In Kerguelen, most of the lavas have been erupted subaerially, and only for the oldest ones in the NKP, 34 Ma old, is there evidence for submarine eruption (Weis and Frey 2002). Drilling on the Kerguelen Archipelago itself would allow for a comparison with Hawaii and for a better understanding of what controls the submarine-subaerial transition and the depth of eruption.

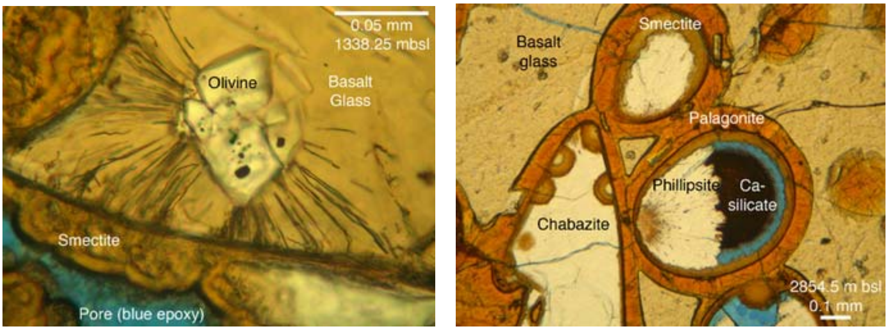

Fig. 7. Alteration features and mineralogy of glass-bearing HSDP samples from 2884 meters below sea level (upper) and 1338 meters below sea level (Walton and Schiffman 2004). A systematic change in mineralogy is found with depth and temperature. Some of the features are thought to be due to micro-organisms living at depths up to about 1500 meters.

3 Large Igneous Provinces in Earth History

Episodic events punctuate Earth history, and large-volume mafic magmatism resulting from processes other than ‘normal’ seafloor spreading and subduction constitute a major class of episodic phenomena (e.g., Coffin and Eldholm 2000; Stein and Hofmann 1994). Such magmatism results in the formation of large igneous provinces (LIPs), which comprise continental flood basalts, volcanic rifted margins, oceanic plateaus, ocean basin flood basalts, submarine ridges, ocean islands, and seamount chains (e.g., Mahoney and Coffin 1997). LIPs have the potential to provide important insights into mantle dynamics as well as to have caused significant environmental changes. First-order, frontier problems in LIP research addressable by drilling include:

Do plume heads cause continental breakup (Courtillot et al. 1999)? The majority of Earth’s divergent continental margins are characterized by thick sequences of mafic volcanic rock that in some instances correlate temporally with adjacent continental flood basalts (Fig. 10). Although there is a distinct correlation, it is not yet understood how anomalously warm and/or upwelling mantle can thermo-mechanically erode the lithosphere and create weak zones susceptible to rifting. An alternative view is that plate divergence is responsible for instigating decompression melting of the mantle, although this should not necessarily produce the large volume of erupted magma observed in many LIPs. Understanding the precise temporal and spatial relationships between tectonics and magmatism via complementary geological (including key drilling), geophysical, and modeling investigations will contribute to addressing this issue.

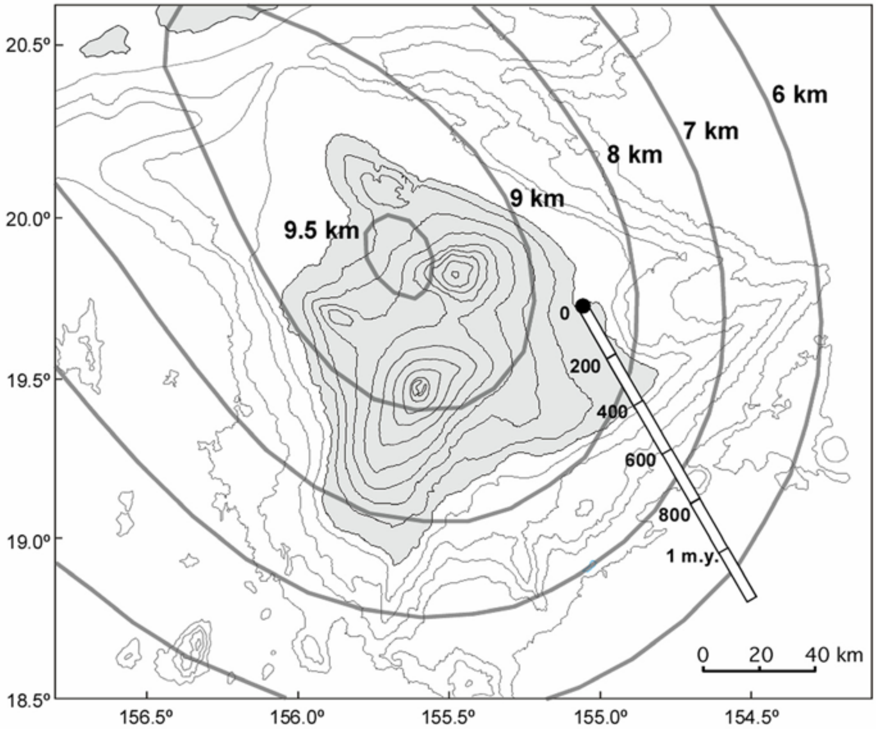

Fig. 8. Estimated contours of depth to the old ocean floor under Hawaii based on lithosphere loading and flexure models (Watts and TenBrink 1988). At the HSDP site there is a precise datum indicating that there has been 1080 m of subsidence since 400,000 years ago. Shown on the figure is the calculated position of the HSDP site for the past 1.2 million years. This track suggests that there should have been about 700 m of subsidence over the past 400,000 years at the HSDP site if the flexure model is correct. The difference is likely to be due to additional deformation that occurs under the volcanoes. More data of this sort, which can only be obtained by drilling, could provide unique constraints on flexure models.

Extraterrestrial impacts and flood volcanism — can bolide impacts instigate massive mantle melting? Bolides have impacted Earth throughout its history, and earth scientists have focused much attention on the global environmental consequences of extraterrestrial impacts. The effects of impacts on the solid earth, however, have been relatively neglected. Recent studies have suggested that the Siberian flood basalts (Jones et al. 2002) and Ontong Java Plateau (Ingle and Coffin 2004) may have formed as a result decompression melting of the mantle induced by bolide impacts. Scrutiny of LIP rocks and contemporary sedimentary sections recovered by drilling, together with complementary modeling studies, may help to answer this fundamental question.

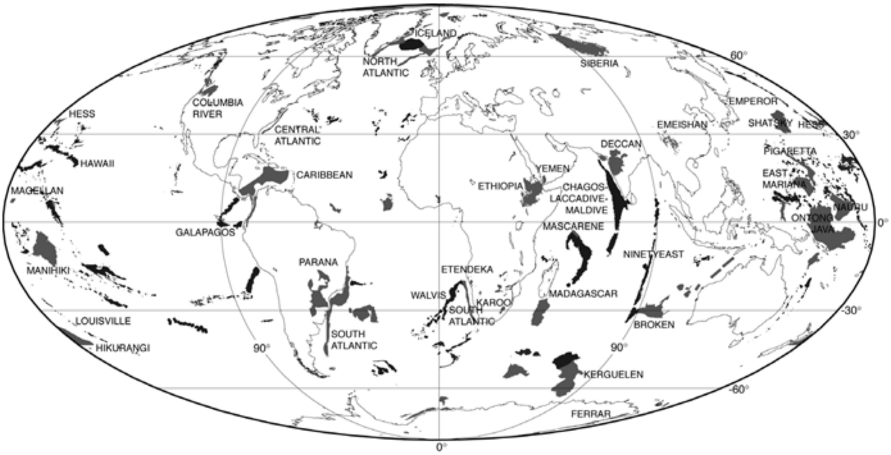

Fig. 9. Global distribution of large igneous provinces (Mahoney and Coffin 1997). Systematic core drilling in most of these provinces could yield important insights into the magma generation process and the nature of the mantle plumes responsible for the volcanism.

Can flood volcanism trigger significant environmental change? Two major mass extinctions of Phanerozoic time, the end-Permian and end-Cretaceous, correlate temporally with emplacement of the Siberian (e.g., Campbell et al. 1992) and Deccan (e.g., Officer and Drake 1985) flood basalts, respectively. Courtillot and Renne (2003) provide evidence for a correlation between the ages of LIPs (CFBs and OPs) and those of mass extinctions and oceanic anoxia events (Fig. 11). Major oceanic anoxic events 1A and 2 correlate temporally with formation of the Ontong Java Plateau (e.g., Larson and Erba 1999) and the Caribbean flood basalts (e.g., Kuroda et al., in prep.), respectively. The Paleocene-Eocene thermal maximum correlates temporally with the peak of Tertiary North Atlantic volcanism (e.g., Eldholm and Thomas 1993; Svensen et al. 2004). Such tantalizing correlations suggest causal relationships; however, copious analyses of drilled basalts and syn-sedimentary sections, as well as much-improved models of environmental change induced by solid earth processes, are required to understand these relationships (Wignall 2001; Courtillot and Renne 2003).

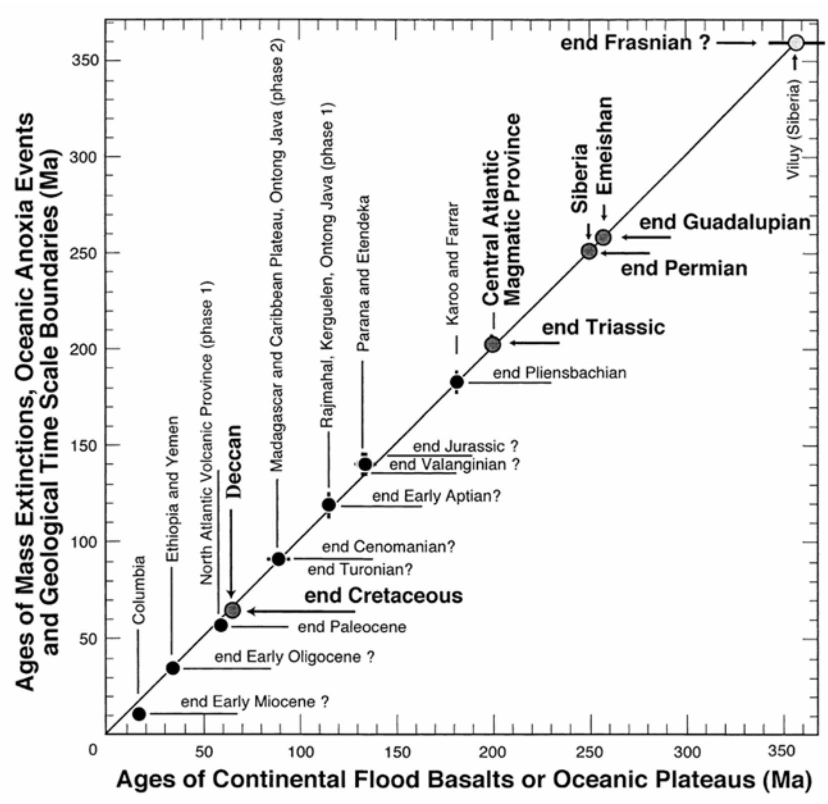

Fig. 10. Correlation between the ages of flood basalt provinces and mass extinctions (all in Ma). The possible causal relationship is still a matter of debate. The figure is taken from Courtillot and Renne (2003).

Many LIPs span the continent-ocean transition (Fig. 10), and cooperative International Continental Drilling Program (ICDP)/Integrated Ocean Drilling Program (IODP) studies will be necessary to advance our understanding of the solid earth and possibly extraterrestrial processes responsible for LIPs and of how intense basaltic volcanism interacts with the atmosphere, hydrosphere, and biosphere.

4 Possible Future Targets for Drilling

4.1 Further Drilling on Oceanic Islands

Although drilling in Hawaii has been successful, it has also raised a number of new questions that could be addressed with targeted drilling elsewhere in Hawaii, and as well as on other oceanic islands. For Hawaii there is evidence that the southwest side of the plume differs from the northeast side (e.g., Abouchami et al. 2005), and there is also evidence that the plume geochemistry changes with time (e.g., Bryce et al. 2005). The Mauna Kea volcano drilled by HSDP shows relatively regular and systematic changes in lava geochemistry with time, but there are larger and less systematic changes that are evident in the available samples from Mauna Loa and Hualalai. Even very shallow drilling in the Koolau volcano has produced unexpected results (Haskins and Garcia 2004). Drilling into the largest volcano in the chain — Haleakala — which also sits at a pronounced change in trend of the island chain, is likely to yield important information about the symmetry and long-term evolution of the Hawaiian plume.

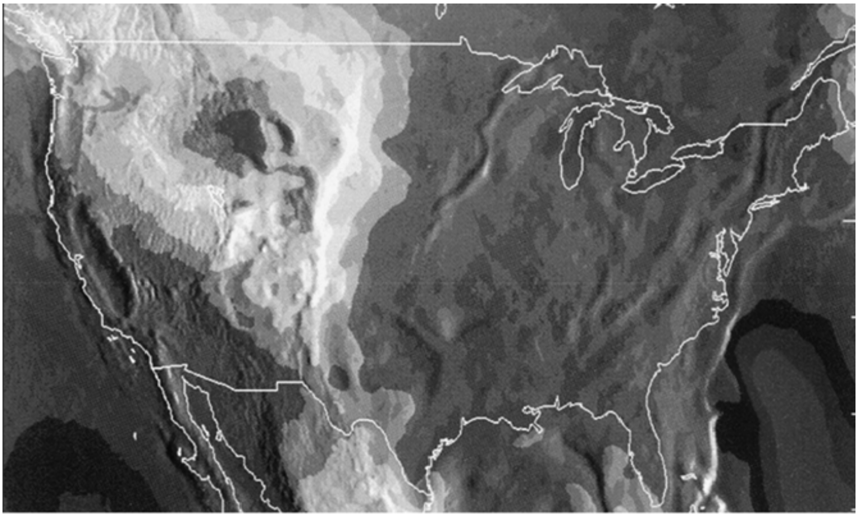

Fig. 11. Geoid map of the continental United States and parts of Canada and Mexico showing the pronounced anomaly centered on the Yellowstone–Snake River Plain area. The Yellowstone region is one of very few examples of an active plume rising under continental lithosphere. Continental drilling results would be enhanced by geophysical imaging of the upper mantle that will be done as part of EarthScope.

Other oceanic volcanoes with different geodynamic contexts would also constitute attractive drilling targets. At present, some of the ocean islands with especially anomalous geochemical characteristics, such as Tristan da Cunha, Reunion, St. Helena, and Samoa, are treated as being equivalent in importance to Hawaii and Iceland (e.g., Zindler and Hart 1986; Hart et al.

2000). Drilling into these islands would be worthwhile to determine if the anomalous geochemistry persists in lavas from deeper in the volcanic piles. It would also be of interest to evaluate the subsidence histories of volcanoes built on oceanic crust of different ages, as well as their hydrology, magmatic processes and biogeochemistry.

Successful drilling on many oceanic islands may not be as easy as in Hawaii. As an example, the rotary drilling done on Reunion in 1985 (Rancon et al. 1989) was able to recover cuttings of only 1 km of stacked lava even though a 3 km hole was drilled. At about 1 km depth the hole entered a region of mostly intrusive rock, which persisted to the bottom of the hole. This experience apparently results from the drilling having been done near the volcano summit, although it was unavoidable due to the subsidence of the island (and the original objective of the drilling; which was geothermal exploration). Under the summit region there is a much higher likelihood of encountering intrusive rocks as well as hydrothermal alteration. For comparison, the Grand Brule drill hole on Piton de la Fournaise was located about 10 km from the summit caldera and encountered mostly intrusives at 1000 m depth whereas the HSDP drill hole was located about 40 km from the summit of Mauna Kea and encountered no significant intrusive bodies down to a depth of 3335 m.

4.2 Snake River Plain

The Snake River Plain (SRP) of southern Idaho has long been associated with the concept of a hot-spot (mantle plume) track which links voluminous flood basalts of the Miocene Columbia River province to Quaternary volcanic centers at Island Park and Yellowstone (Craig 1993). The plume track is marked by a series of rhyolitic eruptive centers that signal the arrival of the hot-spot beneath a new crustal location followed by extensive eruptions of basalts. Existing drill holes in the ESRP show that the basaltic carapace ranges from less than 100 m to over 1000 m thick, with rhyolite basement extending to depths in excess of 3000 m. The plume model has been questioned by recent studies which suggest that these features may be explained by localized asthenospheric upwelling associated with edge effects of North American plate motion and the descending Farallon slab (e.g., Humphreys and Dueker 1994; Humphreys et al. 2000), but the plume model still remains viable for explaining the Cenozoic evolution of western North America, especially considering the large positive geoid anomaly associated with the Yellowstone plateau (Fig. 12).

Core drilling in the Snake River Plain would be timely because it would complement EarthScope-sponsored geophysical studies of continental lithosphere in the northwestern U.S. (USArray and the Plate Boundary Observatory). A systematic series of shallow to intermediate depth drill holes taken along the axis of the Snake River Plain could help test models for the origin and evolution of alleged “plume-related volcanism.” Core samples would also allow for examination of the relationships between rhyolites and basalts, while a series of holes would allow comparison of coeval lavas erupted at different locations along the “plume track.” Drill holes in the SRP could also be instrumented with continuous recording strainmeters and seismometers as part of the PBO and would provide ground-truth observations for crustal and lithospheric studies by the USArray.

Drilling in the Snake River Plain would also be useful for evaluating models of plume-lithosphere interaction. Physical models of plume tail dynamics in continental domains are controversial. Sleep (1990) proposed that topographic relief on the hotspot swell (500 m to 1000 m for Yellowstone) was due entirely to thermal buoyancy. This model predicts that a mantle plume would flatten and spread when confined beneath continental lithosphere, causing a broad circular uplift that would be deformed into a topographic parabola by interaction with the moving lithosphere (Smith and Braile 1994). In contrast, Saltzer and Humphreys (1997) calculate that 20% to 100% of the topographic swell could be compositionally driven, as a result of depletion of the underlying asthenosphere. This implies that no thermal plume is needed to support the observed topographic and geoid swells. Drilling into the SRP basalts would provide critical petrological, geochronological, structural and geochemical data for assessing the plume model and the role of the lithosphere.

4.3 Kerguelen

The Kerguelen mantle plume has been active for at least 120 Myr. The Kerguelen Archipelago is the third largest oceanic island after Hawaii and Iceland and represents part of the Cenozoic volcanic activity of the Kerguelen plume (e.g., Weis et al. 2002). Spreading along the Southeast Indian Ridge (SEIR) over the past ~40 Myr has progressively increased the distance between the SEIR axis and the Kerguelen hotspot; as the ridge moved to the northeast relative to the hotspot, the hotspot evolved from a ridge-centered position to an intraplate location (i.e., Iceland-like to Hawaii-like) (Fig. 13). Field studies of volcanic sections on the archipelago indicate a clear geographic, temporal and compositional trend from the NW tholeiitic-transitional series to the SE alkaline series (Fig. 14). This trend also corresponds to variation in degree of partial melting, magma supply and plume-ridge interaction.

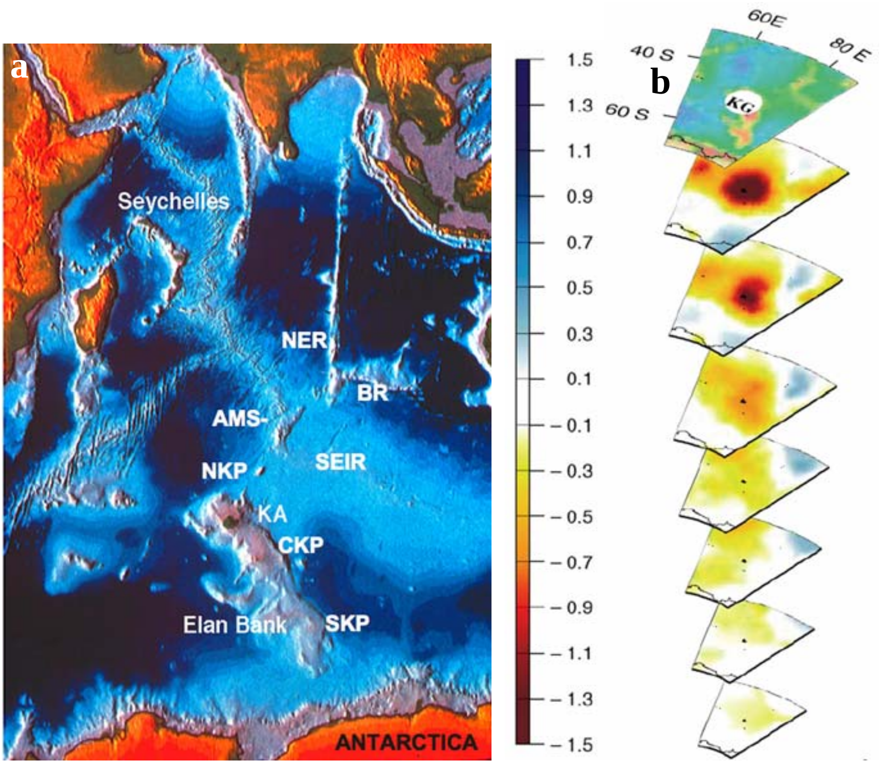

Fig. 12. a. Bathymetric map of the southwestern Indian Ocean indicating the major tectonic features related to the Kerguelen mantle plume volcanism. **b.** The vertical section of p-wave velocity perturbation indicates that the Kerguelen Plume can be imaged all the way down to the core-mantle boundary (Montelli et al. 2004). The color scale for velocity perturbations extends from blue (+1.5% velocity contrast) to red (-1.5% velocity contrast).

Drilling on Kerguelen, although logistically demanding, could lead to extensive new insight into plume processes, mantle structure and magma dynamics. Kerguelen apparently preserves both an initial plume-head phase as well a subsequent long-lived plume tail phase (Fig. 13b). In addition, the volcanic activity has occurred on sequentially older and older oceanic crust. To fully investigate this unique locality will require both an ICDP sponsored project to study the Archipelago, and an IODP sponsored project to study the submarine plateau. This is a rare opportunity to compare plume head and stem volcanism over a time period of 120 Myr.

There are a number of important specific questions that could be answered with drilling at Kerguelen. The magmatic evolution of this province has extended over an extremely long time, especially in comparison to the younger Hawaiian islands for example, and may reveal quite substantial differences with other islands. One straightforward question is how long it has taken for the archipelago flood basalt, covering 85% of the subaerial surface, to form? If the time scale is long enough, there is a possibility that the lavas record the early stage when the Kerguelen Archipelago was coincident with the SEIR at 40 Ma. In a manner vaguely similar to individual Hawaiian volcanoes, the volcanism in Kerguelen has evolved over a long time from mainly tholeiitic to mainly alkalic in composition (e.g., Scoates et al. 2006). However, at present this transition is observed from spatially diverse sections in a NW-SE trend and may be due more to location than age. The tholeiite-alkali basalt transition in Hawaii is clearly related to the plume structure and composition, and the difference in scale at Kerguelen could be highly instructive.

The Kerguelen region lies within the broad expanse of southern ocean territory that is identified with the so-called DUPAL anomaly (Zindler and Hart 1986). This region appears to be underlain in the lower mantle with a region of relatively low seismic velocities (Romanowicz and Gung 2002), which in turn may be the signature of hotter or more geochemically diverse mantle. The Kerguelen lavas, especially because of the longevity of the volcanism, could hold unique clues about the significance of the large scale geochemical structure of the lower mantle, as well as about how plume geochemistry is affected by interaction with mid-ocean ridge mantle and about the role of recycling ancient subcontinental lithospheric mantle or sediments in mantle heterogeneity (e.g., Escrig et al. 2004; Hanan et al. 2004).

Drilling continental flood basalt provinces on-land, such as Deccan, the Siberian traps, Ethiopia or the Parana-Etendeka, might appear easier in terms of logistics but, because of the interactions between the ascending magma and the continental crust, the geochemistry of these lavas is often complicated. Establishing the geochemical signature of the mantle source is therefore more difficult. Nevertheless, continental flood basalt provinces constitute potentially rich natural laboratories for the study of a major class of basaltic volcanism, and limited drill core has already been used in some cases for the study of these lavas (Lightfoot et al. 1993).

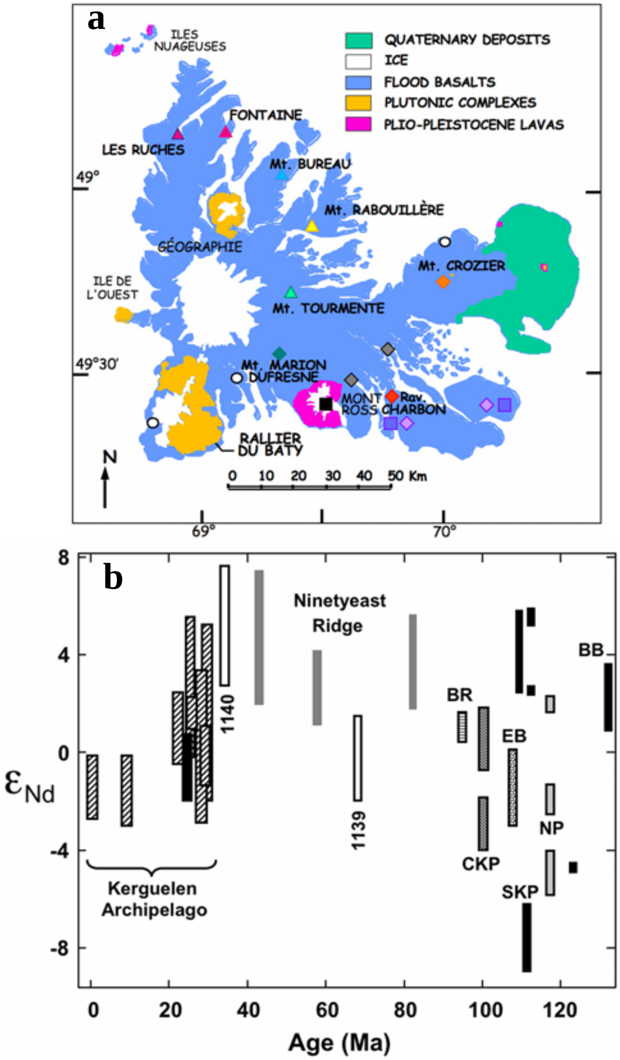

Fig. 13. a. Geological sketch map of the Kerguelen Archipelago. The overall age and composition trend is from 30 Ma tholeiitic basalts in the NW part of the archipelago to 24 Ma alkali basalts in the SE Province. **b.** Age vs. εNd plot shows that the lavas exhibit a large range in isotopic composition, which includes sampling of heterogeneous mantle as well contamination by continental basement that underlies the lava pile and probably is residual from the breakup of Gondwana in the early stages of the Kerguelen plume activity. Kerguelen Archipelago lavas (< 30 Ma) show more limited variations, reflecting mixing between the enriched Kerguelen plume composition and depleted compositions (e.g., NKP, Site 1140, Weis and Frey 2002).

5 Summary and Conclusions

Hot spot volcanic islands and large igneous provinces are attractive targets for continental (on-land) drilling. The volcanic formations are nearly horizontally layered in most cases and drilling allows for the collection of systematic, stratigraphically controlled samples that provide unique records of magmatic processes and mantle structure, lithosphere dynamics, and the thermal, diagenetic, hydrological, and microbiological evolution of the subsurface volcanic environment. Experience with drilling in Hawaii shows that nearly complete core recovery is possible, that penetration rates are reasonably high in many volcanic rocks, and that drilling sites can be identified where the rocks are unaltered and where there are few intrusive rocks. The data that can be obtained by drilling are necessary for developing and testing the next generation of models of mantle magmatism. One of the most important considerations is that the mantle melting under hot spots and LIPs may have come from near the base of the mantle, and therefore the lavas provide geochemical information about the deep Earth that cannot be obtained from any other source. Improvements in geochronology increasingly allow for detailed tests of the relationship between LIPs and other global events, and provide input for new models of hotspot volcano growth and lithosphere deformation. Drilling on oceanic islands also provides unique information on groundwater and seawater aquifers in the basalts, temperature distributions, chemical alteration, and biological activity in the deep subsurface.

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References

Abouchami WA, Hofmann W, Galer SJG, Frey F, Eisele J, Feigenson M (2005) Pb isotopes reveal bilaterial asymmetry and vertical continuity in the Hawaiian plume. Nature 434: 851–856

Armstrong RL, Leeman WP, Malde HE (1975) K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho. The American Journal of Science 275: 225-251

Arndt NT, Christensen U (1992) The role of lithospheric mantle in continental flood basalt volcanism: thermal and geochemical constraints. Journal of Geophysical Research 97: 10,967-10,981

Blichert-Toft J, Weis D, Maerschalk C, Agranier A, Albarède F (2003) Hawaiian hot spot dynamics as inferred from the Hf and Pb isotope evolution of Manua Kea volcano. Geochemistry, Geophysics, Geosystems: 4(2): doi:10.1029/2002GC000340

Boyet M, Carlson RW (2005) ^{142}Nd evidence for early (> 4.53 Ga) global differentiation of the silicate earth. Science 309: 575-581

Brandon AD, Walker RJ, Morgan JW, Norman MD, Prichard HM (1998) Coupled ^{186}Os and ^{187}Os evidence for core-mantle interaction. Science 280: 1570-1573.

Bryce J, DePaolo DJ, Lassiter J (2005) Sr, Nd and Os isotopes in a 2.84 km HSDP2 core of Mauna Kea volcano: Implications for the geochemical structure of the Hawaiian plume. Geochemistry, Geophysics, Geosystems 6(9) doi:10.1029/2004GC000809

Campbell IH, Czamanske GK, Fedorenko VA, Hill RI, Stepanov V (1992) Synchronism of the Siberian Traps and the Permian-Triassic boundary. Science 258: 1760-1763

Christensen UR (1984) Instability in a hot boundary layer and initiation of thermochemical plumes. Annales Geophysicae 2: 311-320

Courtillot VE, Renne PR (2003) On the ages of flood basalt events. Comptes Rendus Geoscience 335: 113-140

Courtillot V, Jaupart C, Manighetti I, Tapponnier P, Besse J (1999) On causal links between flood basalts and continental breakup. Earth and Planetary Science Letters 166: 177-195

Craig H (1993) Yellowstone hotspot: a continental mantle plume. EOS, Transactions, American Geophysical Union 74 (43): 602

Davaille A (2003) Thermal convection in a heterogeneous mantle. Comptes Rendus Geoscience 335: 141-156

Davies GF (1993) Cooling of the core and mantle by plume and plate flows. Geophyical Journal International 115: 132-146

DePaolo DJ (1996) High frequency isotopic variations in the Mauna Kea tholeiitic basalt sequence: melt zone dispersivity and chromatography. Journal of Geophysical Research 101: 11,855-11,864

DePaolo DJ, Manga M (2003) Deep origin of hotspots — the mantle plume model. Science 300: 920-921

DePaoloDJ, Stolper EM (1996) Models of Hawaiian volcano growth and plume structure: Implications of results from the Hawaii Scientific Drilling Project. Journal of Geophysical Research 101: 11,643-11,654

DePaolo DJ, Stolper EM, Thomas DM (1996) The Hawaii Scientific Drilling Project: Summary of Preliminary Results. GSA Today 6(8): 1-8

DePaolo DJ, Stolper EM, Thomas DM (2001a) Deep Drilling into a Hawaiian Volcano. EOS, Transactions, American Geophysical Union 82: 154-155

DePaolo DJ, Bryce JG, Dodson A, Shuster DL, Kennedy BM (2001b) Isotopic evolution of Mauna Loa and the chemical structure of the Hawaiian plume. Geochemistry, Geophysics, Geosystems 2(7): doi:10.1029/2000GC000139

Duncan RA, Richards MA (1991) Hotspots, mantle plumes, flood basalts, and true polar wander. Reviews of Geophysics 29: 31-50

Eisele J, Abouchami W, Galer SJG, Hofmann AW (2003) The 320 kyr Pb isotope evolution of Mauna Kea lavas recorded in the HSDP-2 drill core. Geochemistry, Geophysics, Geosystems 4(5): doi:10.1029/2002GC000339

Eldholm O, Thomas E (1993) Environmental impact of volcanic margin formation. Earth and Planetary Science Letters 117: 319-329

Escrig S, Capmas F, Dupré B, Allègre CJ (2004) Osmium isotopic constraints on the nature of the Dupal anomaly from Indian mid-ocean-ridge basalts. Nature 431: 59-63

Farnetani CG (1997) Excess temperature of mantle plumes: the role of chemical stratification across D”. Geophysical Research Letters 24: 1583-1386

Farnetani CG, Legras B, Tackley PJ (2002) Mixing and deformations in mantle plumes, Earth and Planetary Science Letters 196: 1-15

Fisk MR, Storrie-Lombardi MC, Douglas S, Popa R, McDonald G, Di Meo-Savoie C (2003) Evidence of biological activity in Hawaiian subsurface basalts. Geochemistry, Geophysics, Geosystems 5: 1103, doi.10.1029/2002 GC000387

Frey FA, Coffin MF, Wallace PJ, Weis D, Zhao X, Wise SW, Wahnert V, Teagle DAH, Saccocia PJ, Reusch DN, Pringle M.S., Nicolaysen KE, Neal CR, Muller RD, Moore CL, Mahoney JJ, Keszthelyi L, Inokuchi H, Duncan RA, Delius H, Damuth JE, Damasceno D, Coxall HK, Borre MK, Boehm F, Barling J, Arndt NT, Antretter M (2000) Origin and evolution of a submarine large igneous province: The Kerguelen Plateau and Broken Ridge, Southern Indian Ocean. Earth and Planetary Science Letters 176: 73-89

Geist DJ, Richards M (1993) Origin of the Columbia River plateau and Snake River Plain: deflection of the Yellowstone plume. Geology 21: 789-792

Griffiths RW, Campbell IH (1990) Stirring and structure in mantle starting plumes. Earth and Planetary Science Letters 99: 66-78

Hall PS, Kincaid C (2003) Melting, dehydration, and the dynamics of off-axis plume-ridge interaction. Geochemistry, Geophysics, Geosystems 4(9): 8510, doi:10.1029/2003GC000567

Hanan B, Blichert-Toft J, Pyle DG, Christie DM (2004) Contrasting origins of the upper mantle revealed by hafnium and lead isotopes from the Southeast Indian Ridge. Nature 432: 91-94

Hansen U, Yuen DA (1988) Numerical simulations of thermo-chemical instabilities at the core-mantle boundary. Nature 334: 237-240

Hart SR, Staudigel H, Koppers A, Blusztajn J, Baker E T, Workman R, Jackson M, Hauri E, Kurz M, Sims K, Fornari D, Saal A, Lyons S (2000) Vailulu'u undersea volcano: The New Samoa. Geochemistry, Geophysics, Geosystems 1(12): doi:10.1029/2000GC000108

Haskins EH, Garcia MO (2004) Scientific drilling reveals geochemical heterogeneity within the Koolau shield, Hawaii. Contributions to Mineralogy and Petrology 147: 162-188

Hauri E (1996) Major-element variability in the Hawaiian mantle plume. Nature 382: 415-419

Hill RI, Campbell IH, Davies GF, Griffiths RW (1992) Mantle plumes and continental tectonics. Science 256: 186-193

Hofmann AW (1997) Mantle chemistry: the message from oceanic volcanism. Nature 385: 219-229

Hofmann AW (2003) Sampling mantle heterogeneity through oceanic basalts: isotopes and trace elements. In: Carlson RW (ed) The Mantle and Core, Treatise on geochemistry, Vol. 2, pp 61-101

Hofmann AW, White WM (1982) Mantle plumes from ancient oceanic crust. Earth and Planetary Science Letters 57: 421-436

Humphreys ED, Dueker KG (1994) Western U.S. upper mantle structure. Journal of Geophysical Research 99: 9615-9634

Ingle SP, Coffin MF (2004) Impact origin for the greater Ontong Java Plateau? Earth and Planetary Science Letters 218: 123-134

Ito G, Lin J, Graham D (2003) Observational and theoretical studies of the dynamics of mantle plume-mid-ocean ridge interaction. Reviews of Geophysics 41(4): 1017, doi:10.1029/2002RG000117

Jeanloz R (1993) Chemical reactions at Earth’s core-mantle boundary: Summary of evidence and geomagnetic implications. In: Aki K, Dmowska R (eds) Relating Geophysical Structures and Processes: The Jeffreys Volume, Geophysical Monograph 76, American Geophysical Union, Washington DC, USA, pp 121-127

Jellinek AM, Manga M (2002) The influence of a chemical boundary layer on the fixity, spacing and lifetime of mantle plumes. Nature 418: 760-763

Jones AP, Price GD, Price NJ, DeCarli PS, Clegg RA (2002) Impact induced melting and the development of large igneous provinces. Earth and Planetary Science Letters 202: 551-561

Kellogg LH, King S (1993) Effect of mantle plumes on the growth of D” by reaction between the core and mantle. Geophysical Research Letters 20: 379-382

Kerr RC, Meriaux C (2004) Structure and dynamics of sheared mantle plumes. Geochemistry, Geophysics, Geosystems 5(12): Q12009, doi:10.1029/2004GC000749

Kiefer WS, Hager BH (1991) A mantle plume model for the equatorial highlands of Venus. Journal of Geophysical Research 96: 20,947-20,966

Kontny A, Vahle C, de Wall H (2003) Characteristic magnetic behavior of subaerial and submarine lava units from the Hawaiian Scientific Drilling Project

(HSDP-2). Geochemistry, Geophysics, Geosystems 4(2): 8703, doi:10.1029/2002GC000304

Kuroda J, Ogawa NO, Tanimizu M, Coffin MF, Tokuyama H, Kitazato H, Ohkouchi N (in preparation) Massive volcanism of large igneous provinces as a causal mechanism for a Cretaceous Oceanic Anoxic Event. Nature

Kurz MD, Curtice J, Lott III DE, Solow A (2004) Rapid helium isotopic variability in Mauna Kea shield lavas from the Hawaiian Scientific Drilling Project. Geochemistry, Geophysics, Geosystems 5: Q04G14, doi:10.1029/2002GC 000439

Larson RL, Erba E (1999) Onset of the mid-Cretaceous greenhouse in the Barremian-Aptian: igneous events and the biological, sedimentary, and geochemical responses. Paleoceanography 14: 663-678

Lightfoot PC, Hawkesworth CJ, Hergt J, Naldrett AJ, Gorbachev NS, Fedorenko VA, Doherty W (1993) Remobilization of the continental lithosphere by a mantle plume — major-element, trace-element, and Sr-isotope, Nd-isotope, and Pb-isotope evidence from picritic and tholeiitic lavas of the Norilsk district, Siberian Trap, Russia. Contributions to Mineralogy and Petrology 114 (2): 171-188

Mahoney JJ, Coffin MF (eds) (1997) Large igneous provinces: continental, oceanic, and planetary flood volcanism. Geophysical Monograph, volume 100, American Geophysical Union, Washington DC, USA, 438 pp

Moore JG (1987) Subsidence of the Hawaiian Ridge. U.S. Geological Survey Professional Paper 1350: 85-100

Moore JG, Clague DA (1992) Volcano growth and evolution of the island of Hawaii. Geological Society of America Bulletin 104: 1471-1484

Montelli R, Nolet G, Dahlen FA, Masters G, Engdahl ER, Shu-Huei Hung S-H (2004) Finite-Frequency Tomography Reveals a Variety of Plumes in the Mantle. Science 303: 338-343

Morgan WJ (1971) Convection plumes in the lower mantle. Nature 230: 42-43

Morgan WJ (1981) Hotspot tracks and the opening of the Atlantic and Indian oceans. In: Emiliani C (ed) The oceanic lithosphere, in the series, The sea, ideas and observations on progress in the study of the seas, Volume 7, J Wiley & Sons, New York NY, pp 443-489

Nicolaysen K, Frey FA, Weis D, Hodges K, Giret A (2000) ^{40}Ar/^{39}Ar Geochronology of flood basalts, from the Kerguelen Archipelago, southern Indian Ocean: implications for Cenozoic eruptive rates of the Kerguelen plume. Earth and Planetary Science Letters 174: 313-328

Norman MD, Garcia MO, Kamenetsky VS, Nielsen RL (2002) Olivine-hosted melt inclusions in Hawaiian picrites: Equilibration, melting, and plume source characteristics. Chemical Geology 183: 143-168

Officer CB, Drake CL (1985) Terminal Cretaceous environmental events. Science 227: 1161-1167

Rancon JP, LeRebour P, Auge T (1989) The Grand Brule exploration drilling — new data on the deep framework of the Piton-de-la-Fournaise volcano. 1. Lithostratigraphic units and volcanostructural implications. Journal of Volcanology and Geothermal Research 36: 113-127

Rhodes JM, Vollinger MJ (2004) Composition of basaltic lavas sampled by phase-2 of the Hawaii Scientific Drilling Project: Geochemical stratigraphy and magma types. Geochemistry, Geophysics, Geosystems 5: Q03G13, doi:10.1029/2002GC000434

Ribe NM, Christensen UR (1999) The dynamical origin of Hawaiian volcanism. Earth and Planetary Science Letters 171: 517-531

Richards MR, Duncan R, Courtillot V (1989) Flood basalts and hot-spot tracks: plume heads and tails. Science 246: 103-107

Romanowicz B, Gung YC (2002) Superplumes from the core-mantle boundary to the lithosphere: Implications for heat flux. Science 296: 513-516

Saltzer RL, Humphreys ED (1997) Upper mantle P wave velocity structure of the eastern Snake River plain and its relationship to geodynamic models of the region. Journal of Geophysical Research 102: 11,829-11,841

Samuel H, Farnetani CG (2003) Thermochemical convection and helium concentrations in mantle plumes. Earth and Planetary Science Letters 207: 39-56

Schilling J-G (1991) Fluxes and excess temperatures of mantle plumes inferred from their interaction with migrating midocean ridges. Nature 352: 397-403

Scoates JS, Lo Cascio M, Weis D, Lindsley DH (2006) Experimental Constraints on the Origin and Evolution of Mildly Alkalic Basalts from the Kerguelen Archipelago, Southeast Indian Ocean. Contributions to Mineralogy and Petrology 151: 582-599

Sharp WD, Renne PR (2005) The Ar-40/Ar-39 dating of core recovered by the Hawaii Scientific Drilling Project (phase 2), Hilo, Hawaii. Geochemistry, Geophysics, Geosystems 6: Q04G17, doi:10.1029/2004GC000846

Sharp WD, Turrin BD, Renne PR, Lanphere MA (1996) The ^{40}Ar/^{39}Ar and K/Ar dating of lavas from the Hilo 1-km core hole, Hawaii Scientific Drilling Project. Journal of Geophysical Research 101: 11,607-11,616

Sleep NH (1990) Hotspots and mantle plumes: Some phenomenology. Journal of Geophysical Research 95: 6715-6736

Smith RB, Braile LW (1994) The Yellowstone hotspot. Journal of Volcanology and Geothermal Research 61: 121-187

Steinberger B, O’Connell RJ (1998) Advection of plumes in mantle flow — Implications for hotspot motion, mantle viscosity and plume distribution. Geophysical Journal International 132: 412-434

Stolper EM, DePaolo DJ, Thomas DM (1996) The Hawaii Scientific Drilling Project: Introduction to the Special Section. Journal of Geophysical Research 101: 11,593-11,598

Stolper EM, Sherman S, Garcia M, Baker M, Seaman C (2004) Glass in the submarine section of the HSDP2 drill core, Hilo, Hawaii. Geochemistry, Geophysics, Geosystems 5: Q07G15, doi:10.1029/2003GC000553

Svensen H, Planke S, Malthe-Sørenssen A, Jamtveit B, Myklebust R, Rasmussen T, Rey SS (2004). Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. Nature 429: 542-545

Thomas DM, Paillet FL, Conrad ME (1996) Hydrogeology of the Hawaii Scientific Drilling Project borehole KP-1, 2, Groundwater geochemistry and regional flow patterns, Journal of Geophysical Research 101: 11,683-11,694

Van Keken P (1997) Evolution of starting mantle plumes — A comparison between numerical and laboratory models. Earth and Planetary Science Letters 148: 1-11

Walker GPL (1990) Geology and volcanology of the Hawaiian Islands. Pacific Science 44: 315-347

Walton AW, Schiffman P (2003) Alteration of hyaloclastites in the HSDP2 Phase 1 drill core: 1. Description and paragenesis. Geochemistry, Geophysics, Geosystems 5: 8709, doi.10.1029/2002GC000368

Watson S, McKenzie DP (1991) Melt generation by plumes: a study of Hawaiian volcanism. Journal of Petrology 32: 501-537

Watts AB (2001) Isostasy and Flexure of the Lithosphere. Cambridge University Press, Cambridge UK, 478 pp

Weis D, Frey FA (2002) Submarine Basalts of the Northern Kerguelen Plateau: Interaction Between the Kerguelen Plume and the Southeast Indian Ridge Revealed at ODP Site 1140. Journal of Petrology 43: 1287-1309

Weis D, Frey FA, Schlich R, Schaming M, Montigny R, Damasceno D, Mattielli N, Nicolaysen KE, Scoates JS (2002) Trace of the Kerguelen Mantle Plume: Evidence from seamounts between the Kerguelen Archipelago and Heard Island, Indian Ocean. Geochemistry, Geophysics, Geosystems 3(6): doi:10.1029/2001GC000251

White RS (1993) Melt production rates in mantle plumes. Philosophical Transactions of the Royal Society of London Series A, 342: 137-153

Zindler AE, Hart S (1986) Chemical geodynamics. Annual Review of Earth and Planetary Sciences 14: 493-571