Geochemical Structure of the Hawaiian Plume: Results from the Hawaii Scientific Drilling Project

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The major focus of the Hawaii Scientific Drilling Project is the recovery and characterization of a continuous set of lava samples from a single Hawaiian volcano. These samples provide a unique opportunity to test aspects of the mantle plume hypothesis. In 1993 a 1.06 km pilot corehole was drilled into the flank of the Mauna Kea volcano at Hilo (Stolper et al., 1996). In 1999, a 3.1 km corehole was drilled at a site 2 km south of the site of the 1993 drilling with nearly complete core recovery. In 2003 the hole is being deepened with the hope of reaching 4.5 km. The project is funded by the U.S. National Science Foundation and the International Continental Drilling Program (ICDP; http://www.icdp-online.de/).

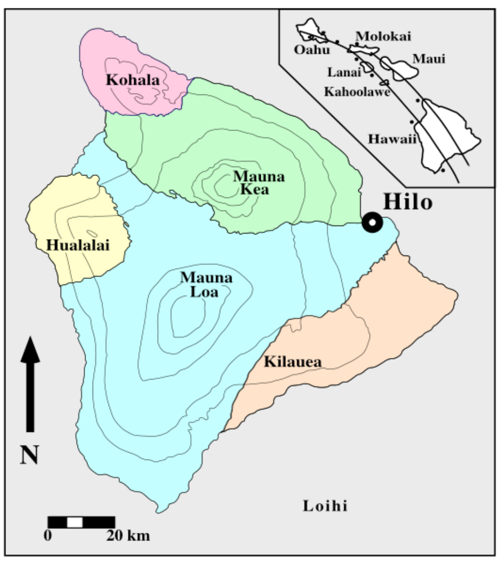

Figure 1. (left) Location map for the Hawaii Scientific Drilling Project 1.06 km pilot hole and 3.1km deep hole. (right) Drill rig in operation in Hilo in 1999.

The drillsite was chosen to be (1) far from volcanic rift zones to minimize chances of encountering intrusive rocks, alteration, and high-temperature fluids, (2) close to the coastline, to minimize the thickness of subaerial lavas that would need to be penetrated to reach the older, submarine parts of the Mauna Kea section, and (3) in an industrial area to minimize environmental and community impacts. Although the Mauna Kea lava section was the primary target, this choice of site required drilling through a 280m - thick section of ML flows, thereby providing additional information on the Mauna Loa volcanic succession. Temperatures in the upper part of the hole are indeed low; circulation of seawater through the volcanic pile causes the temperature to decrease with depth to a low of 12°C at about 800m depth, whereupon it begins to increase to 45°C at 3.1 km. Alteration is minimal. Intrusives were successfully avoided; they make up less than 2% of the core, but the percentage increases gradually in the lowermost part of the core. Digital photographs of each core box, high-resolution scans of the core, a detailed lithological column, and detailed descriptions of the entire recovered core can be accessed at http://icdp.gfz-potsdam.de/html/hawaii/news.html.

A major focus of our effort has been a comprehensive geochemical and petrological characterization of the samples recovered from the core. In both the pilot hole and HSDP-2, a "reference set" of over 100 samples were distributed to investigators from around the world. In addition to the reference suite, which samples the section at 50-100 m intervals, for the submarine section fresh glass samples were prepared at intervals of about 3 m. A simplified lithologic section of the core and the available age data are shown in Figure 2.

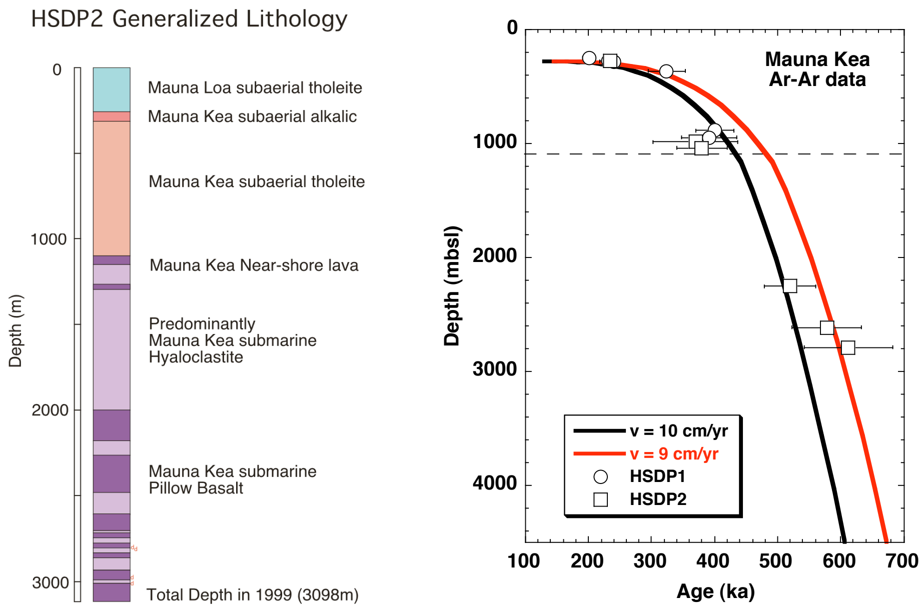

Figure 2; Generalized lithologic section of the 3.1 km HSDP core and Ar-Ar age data with 1sigma uncertainties (Sharp et al., 1996, 2003). At this scale depth in the hole (m) and depth in meters below sea level (mbsl) are approximately the same; the hole was drilled at an elevation 11m above sea level. The Argon age data are shown with two model lava accumulation rate curves based on the models of DePaolo and Stolper (1996). The parameter "v" is the plate velocity in the reference plane of the plume. DePaolo et al. (2001) speculate that the plume may be wobbling relative to a "fixed" reference frame.

The cored section includes about 250 m of Mauna Loa tholeiitic lavas varying in age from 2 to about 80 - 100 ka. The Mauna Kea section comprises subaerial flows between 250 and 1080 meters, mostly well-indurated basaltic submarine hyaloclastite from 1080 to 2000 meters, and pillow basalt with intercalated hyaloclastite from 2000 to 3098 meters. The Ar-Ar age data indicate that the age of lavas at 3098 m depth is about 600 ka. Hence the core plus subaerial exposures of Mauna Kea lavas provide a continuous record of the volcano for 600,000 years. Figure 3 shows the calculated track of the Mauna Kea volcano summit relative to a model Hawaiian plume melt production zone. The geochemical stratigraphy covers about 60% of the Mauna Kea traverse of the melting region, and encompasses the transition from tholeiitic to alkaline lavas, which is accompanied by a major decrease in eruption rate.

Examples of isotope stratigraphy, shown in Figure 4, in general show systematic shifts with age in the directions expected for a model of a radially zoned plume. Helium and ^{208}Pb show the largest shifts, but even the Nd shifts are systematic although small. Hafnium shows a deviation from expected behavior in the uppermost, alkalic and transitional lavas erupted between 300 and 200 ka. There is little change in the isotopic composition of the magma sources during the transition from tholeiitic to alkaline lavas, except possibly for Hf isotopes. The lava major element compositions are divisible into high- and low-silica groups (Rhodes et al., 2003, Stolper et al. 2003) isotopic differences between the groups are small.

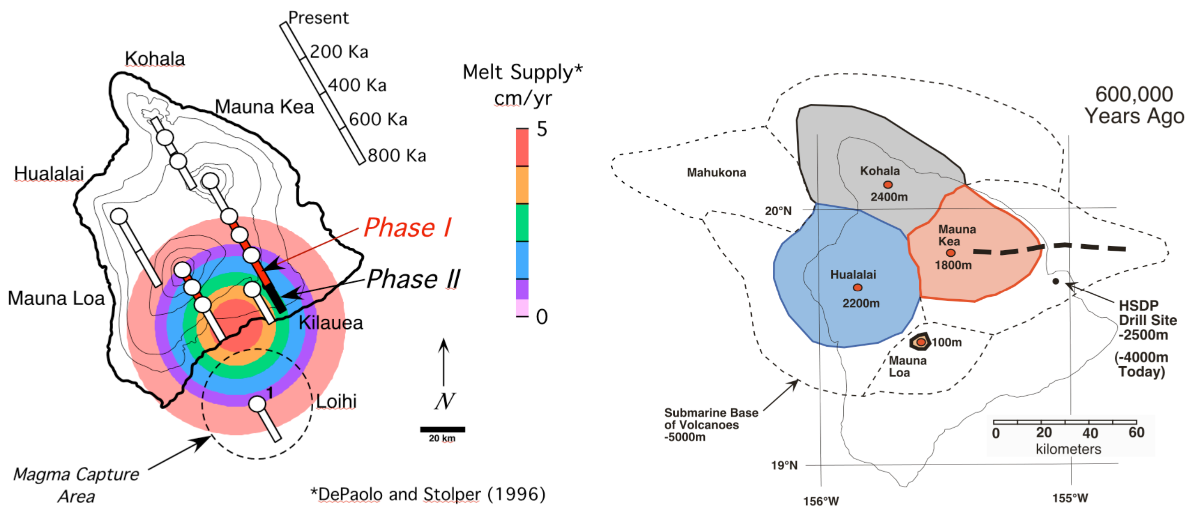

Figure 3: (left) Map showing inferred past positions of volcano summits relative to the melting anomaly that constitutes the Hawaiian mantle plume (DePaolo et al., 2001). At progressively greater times in the past, the volcanoes were farther to the southeast due to the movement of the Pacific plate. The HSDP core drilling retrieved lavas from Mauna Kea and Mauna Loa that represent the summit position tracks indicated by the filled lines colored in red. The black filled line segment shows the portion of the Mauna Kea track that will be covered by the next phase of HSDP drilling. (right) Probable configuration of the island at 600 ka, showing submarine location of the Hilo drill site.

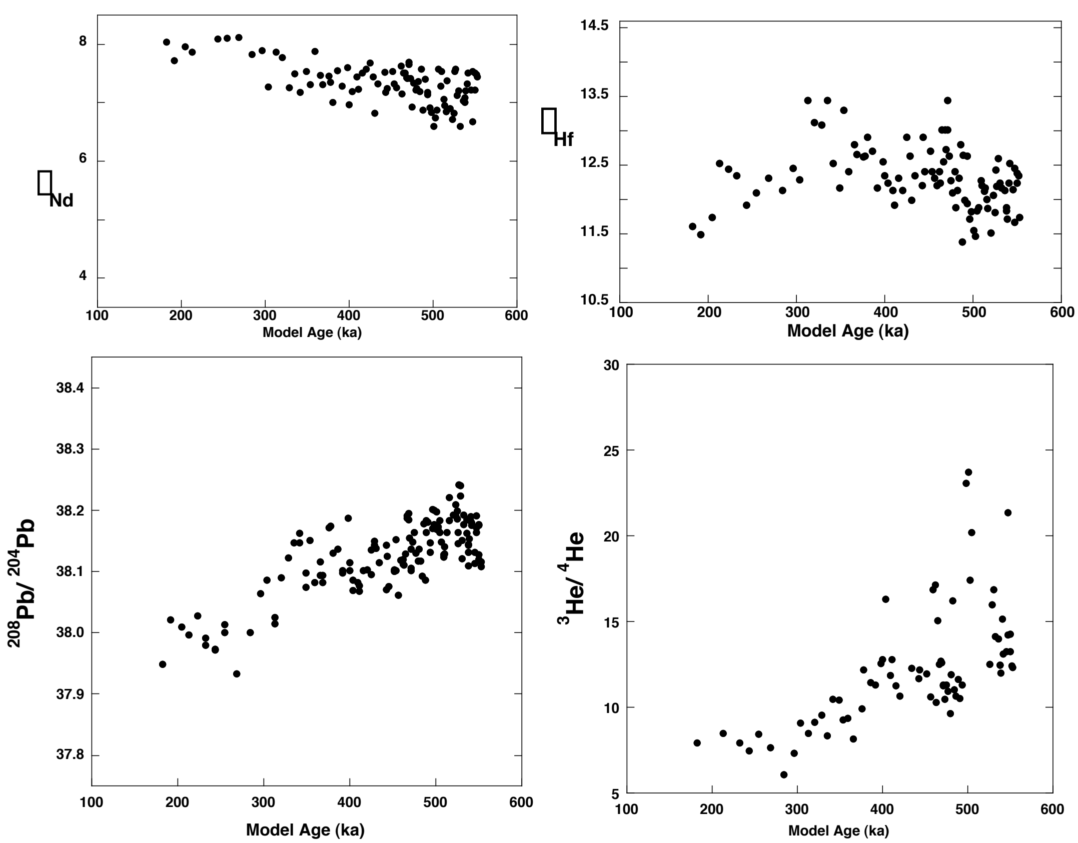

Figure 4: Plots of isotopic ratio versus age for lava samples from the 1999 HSDP2 core. The oldest lavas are at a depth of ca. 3090m below sea level. The total vertical extent of each diagram corresponds to the range of isotopic compositions reported for the volcanoes of the big island of Hawaii. (Data from Eisele et al., 2003; Blichert-Toft et al., 2003; Kurz et al., 2003; Bryce et al, 2003)

A model based on the melt generation pattern shown in Figure 3 is being used to evaluate the data. The objective is to account for the age and volume of the volcanoes of the Big Island, the lava accumulation rate of Mauna Kea (Figure 2), and the geochemical stratigraphy. The major uncertainty is in how the plume melts are sampled by individual volcanoes. We assign to each volcano the melts produced within a circular area of radius 25km centered on the summit (Fig. 3). This model is able to account for the volcano volumes as well as the geochemistry. The model lava accumulation rates are shown in Figure 2. The model requires that the radius of the geochemically anomalous material at the plume core is about 2/3 the radius of the melting region, and about 40% of the radius of the temperature anomaly. Comparison of data from Mauna Loa and Mauna Kea also shows that the plume core is longitudinally heterogeneous. There does not appear to be much longitudinal heterogeneity in the outer parts of the plume melting region, as the Kea trend volcanoes have a highly consistent isotopic composition over $> 10^6$ years. The radial structure of the plume may reflect the vertical structure of the mantle it has traversed, and implies that the lowermost mantle (plume source) is highly heterogeneous, whereas the mid-mantle is both less heterogeneous and more depleted, although not as depleted as the NMORB source.

Current models for the Hawaiian plume require upwelling velocities at the core of the plume that are upwards of 30 cm/yr, depending on the viscosity structure. To generate enough melt per unit time to construct the volcanoes, the maximum potential temperature (□) must be about 1550°C or somewhat higher, and the maximum extent of melting (F) must be about 20%. There is some tradeoff between upwelling velocity versus □ and F. Both the major element compositions of the HSDP lavas (Stolper et al., 2003) and the trace elements (Feigenson et al., 2003; Huang and Frey, 2003) are consistent with the geodynamically-inferred parameters.

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