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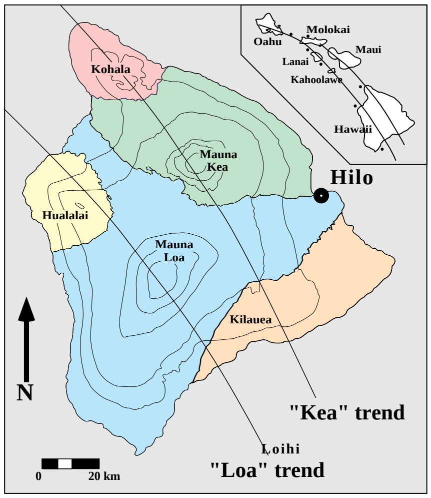
INSIDE

Hawaii Scientific Drilling Project: Summary of Preliminary Results

*Hawaii Scientific Drilling Project Team**



ABSTRACT

Petrological, geochemical, geomagnetic, and volcanological characterization of the recovered core from a 1056-m-deep well into the flank of the Mauna Kea volcano in Hilo, Hawaii, and downhole logging and fluid sampling have provided a unique view of the evolution and internal structure of a major oceanic volcano unavailable from surface exposures. Core recovery was ~90%, yielding a time series of fresh, subaerial lavas extending back to ~400 ka. Results of this 1993 project provide a basis for a more ambitious project to core drill a well 4.5 km deep in a nearby location with the goal of recovering an extended, high-density stratigraphic sequence of lavas.

INTRODUCTION

Intraplate or "hot-spot" volcanic island chains, exemplified by Hawaii, play an important role in plate-tectonic theory as reference points for absolute plate motions. The origin of hot spots, however, is not explained by the plate tectonic paradigm. The most widely held view is that hot-spot volcanoes represent magma generated by decompression melting of localized, buoyant upwellings in the mantle. These upwellings, or "plumes," are believed to originate at boundary layers in the mantle, and the cause of the buoyancy may be both compositional and thermal. Mantle plumes represent a secondary form of mantle convection and constitute an important mechanism for cycling mass from the deep

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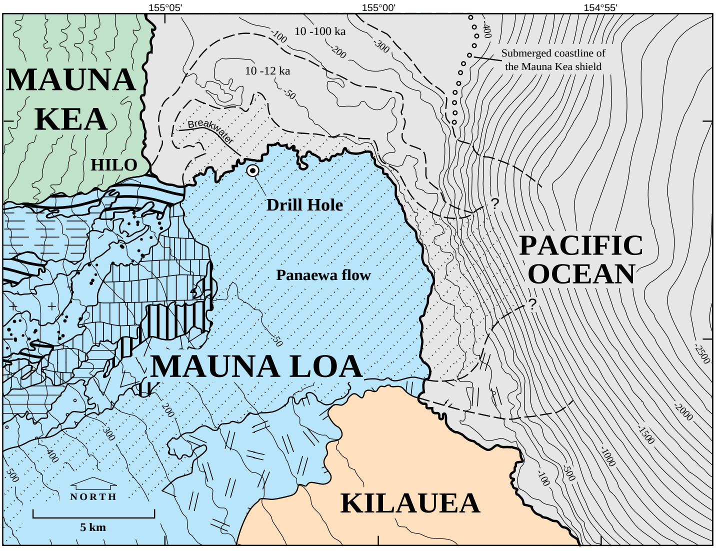

Figure 1. Top: The Hawaiian Islands (inset) and island of Hawaii showing volcanoes in the "Loa" and "Kea" trends and the location of the HSDP pilot hole at Hilo. Bottom: Geologic map of the Hilo vicinity showing location of the pilot hole. After Lipman and Moore (1996).

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mantle to Earth's surface. Studies of the chemical and isotopic compositions of intraplate lavas, especially from ocean-island volcanoes, have contributed significantly to our knowledge of magma genesis and compositional heterogeneity in the mantle. Of particular importance is the identification of distinct compositional mantle end members, the origin and distribution of which provide insights into differentiation of the mantle-crust system, recycling of oceanic crust and continent-

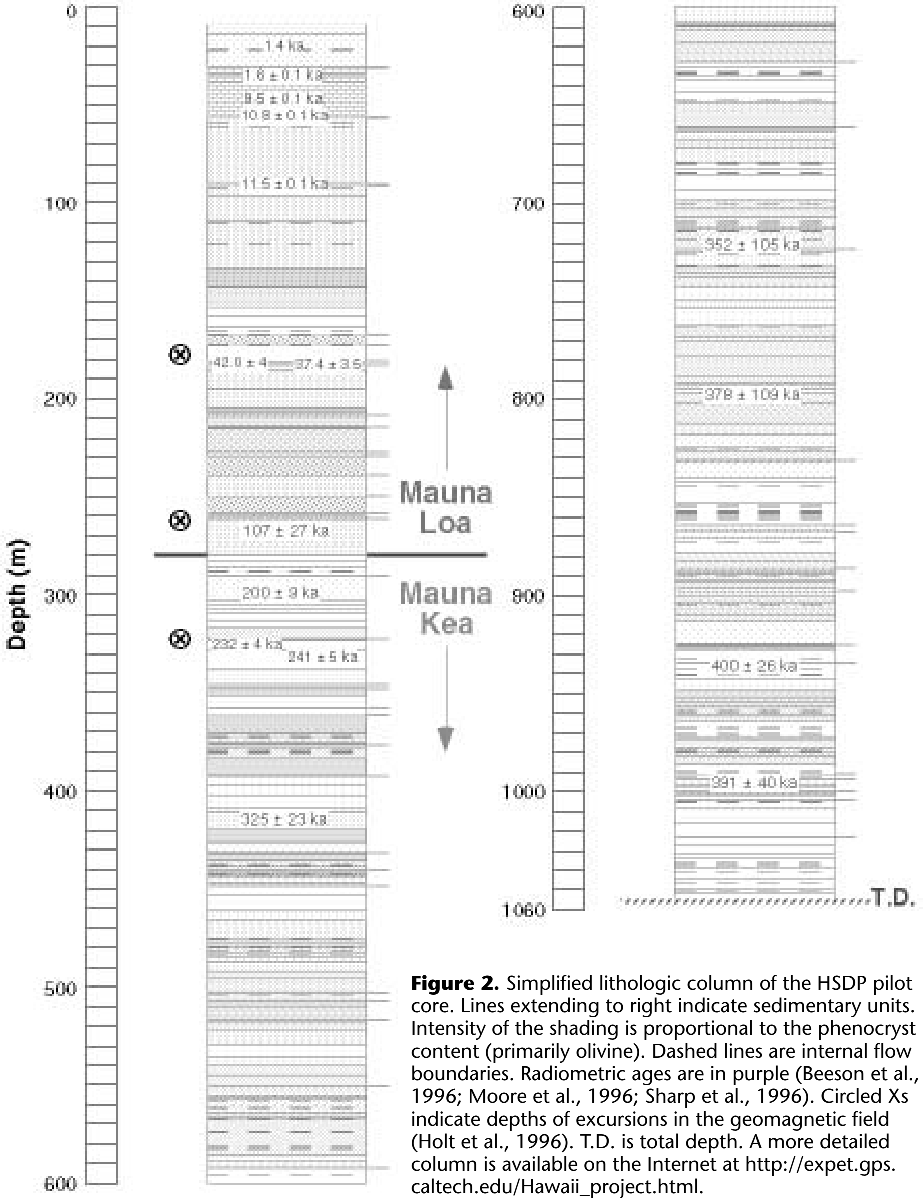

Figure 2. Simplified lithologic column of the HSDP pilot core. Lines extending to right indicate sedimentary units. Intensity of the shading is proportional to the phenocryst content (primarily olivine). Dashed lines are internal flow boundaries. Radiometric ages are in purple (Beeson et al., 1996; Moore et al., 1996; Sharp et al., 1996). Circled Xs indicate depths of excursions in the geomagnetic field (Holt et al., 1996). T.D. is total depth. A more detailed column is available on the Internet at http://expet.gps.caltech.edu/Hawaii_project.html.

derived sediment into the mantle, and lithospheric history.

An intraplate oceanic volcano can be viewed as a probe, sampling magmas produced by melting of the plume as the oceanic plate carries the volcano over the plume and recording this output in stratigraphic succession in its lavas. Sampling and analysis of an extended part of such a succession of lava flows would provide critical information on mantle plume structure and origin. However, a limitation in the study of hot-spot volcanoes is that the major volume of each volcano is inaccessible because it is below sea level. Even for those parts of oceanic volcanoes above sea level, erosion typically exposes only a few hundred meters of buried lavas (out of a total thickness of 6–20 km). For example, although the Hawaiian-Emperor chain has been active for at least 70 m.y., all we can generally examine for any individual volcano is that small fraction (5%–10%) of its history for which evidence is now exposed subaerially. Thus, although the late stages of Hawaiian volcanoes can be studied and viewed as a time sequence, the evolution of a single volcano during its ~1 m.y. passage across the plume is almost entirely inaccessible. If sequences of lava flows from ocean-island volcanoes spanning sufficiently long time periods could be collected, they could be uniquely valuable as probes of plume structure and related magmatic processes. Continuous core drilling through a lava sequence on the flank of an oceanic volcano is probably the only way to obtain such a stratigraphic sequence.

Hawaii Scientific Drilling Project

In recognition of the opportunities afforded by drilling through the flank of an oceanic volcano, the Hawaii Scientific Drilling Project (HSDP) was conceived in the mid-1980s to core continuously to a depth of several kilometers in the flank of the Mauna Kea volcano (DePaolo et al., 1991). Hawaii is the natural target because it is the archetype of ocean-island volcanism.

Core drilling of the "pilot hole" in Hilo, Hawaii, was done by Tonto Drilling Services, Inc. (Salt Lake City, Utah) from October to December 1993. The following 18 months were devoted to petrological, geochemical, geomagnetic, and volcanological characterization of the recovered core and the downhole logging and fluid-sampling program. In addition to these primary scientific goals, the "pilot hole" served as a test bed for a more ambitious, several-kilometer-deep-core hole by demonstrating the technical feasibility of the drilling program and the ability of the multidisciplinary, international group of project scientists to work together effectively. The pilot hole was funded by the National Science Foundation Continental Dynamics Program.

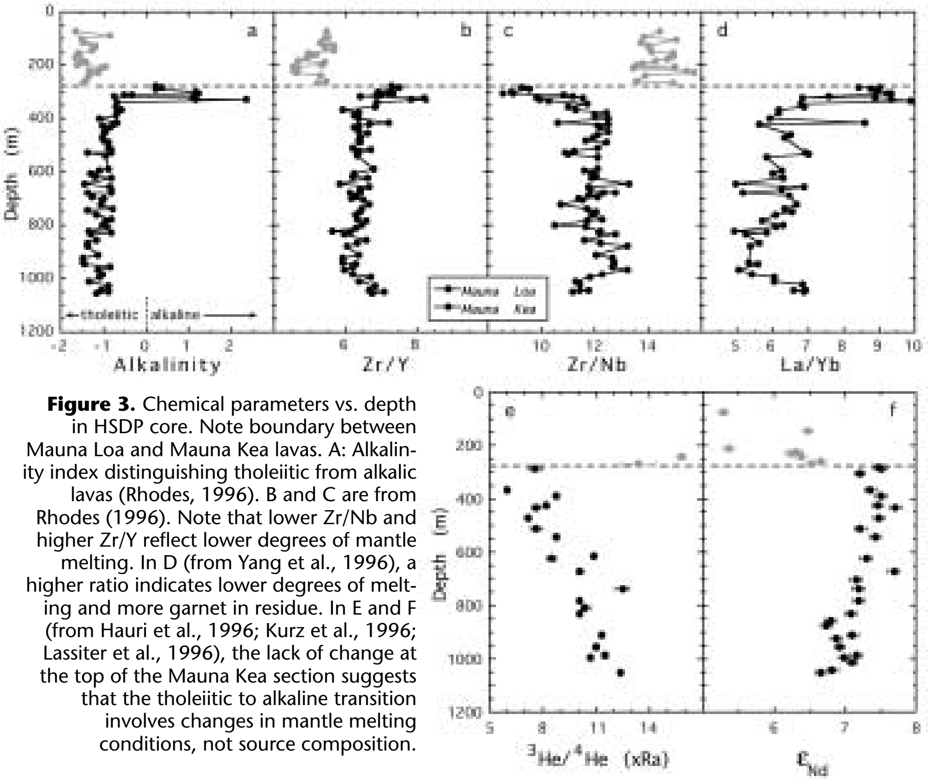

Figure 3. Chemical parameters vs. depth in HSDP core. Note boundary between Mauna Loa and Mauna Kea lavas. A: Alkalinity index distinguishing tholeiitic from alkalic lavas (Rhodes, 1996). B and C are from Rhodes (1996). Note that lower Zr/Nb and higher Zr/Y reflect lower degrees of mantle melting. In D (from Yang et al., 1996), a higher ratio indicates lower degrees of melting and more garnet in residue. In E and F (from Hauri et al., 1996; Kurz et al., 1996; Lassiter et al., 1996), the lack of change at the top of the Mauna Kea section suggests that the tholeiitic to alkaline transition involves changes in mantle melting conditions, not source composition.

The HSDP pilot hole drill site was near Hilo Bay on the ~1400-year-old Panaewa flow series from Mauna Loa volcano (Fig. 1). The site was chosen to (1) be far from volcanic rift zones to minimize chances of encountering intrusion, alteration, and high-temperature fluids; (2) be close to the coastline, to maximize the probability of encountering submarine flow units and relatively old lavas; and (3) drill through some Mauna Loa lavas before encountering Mauna Kea lavas, to test our ability to distinguish between lavas of different volcanoes. Other factors were related to permitting and avoiding disturbance of the community.

Drilling lasted 46 days, reaching a total depth of 1056 m at an average penetration rate of >20 m per day. The penetration rate during periods of drilling (excluding logging time, waiting for cement, etc.) was ~30 m per day. Core recovery for the hole averaged about 90%; major losses occurred in unconsolidated sediments not effectively captured by the core barrel and in rubble zones that jammed the core barrel.

DESCRIPTION OF THE STRATIGRAPHIC SECTION

Core logging led to the designation of the 227 units in the generalized lithologic section in Figure 2. Of these, 208 are lava flows; the rest are ash beds, marine and beach sediments, and soils. No intrusive units have been identified. The location of the contact between Mauna Loa and Mauna Kea lavas at a depth of 280 m is unambiguous. Evidence comes from: (1) abrupt changes in trace element and He, O, Sr, Pb, and Nd isotopic ratios (Fig. 3); (2) projection of the exposed slope of Mauna Kea to depth; (3) lava flows shallower than 280 m being interlayered with nearshore sediments and systematically thicker than those below, as expected for Mauna Loa lavas erupted as gently sloping lava deltas extending into Hilo Bay rather than for Mauna Kea lavas erupted on steep slopes well above sea level; (4) a significant soil horizon at the geochemically defined boundary; (5) intercalation of alkalic and tholeiitic lavas in the 50 m below the geochemically defined boundary, consistent with the end of shield building at Mauna Kea (Fig. 3); and (6) major element compositions of tholeiites above and below the contact being consistent with known differences between Mauna Loa and Mauna Kea lavas.

All sampled Mauna Kea lavas have been interpreted as subaerial, not submarine. The discovery of subaerial lavas more than 1 km below current sea level is not surprising, because Hawaii is subsiding at a rate of 2.0–2.5 mm/yr (Moore, 1987). At this rate, the minimum age of the lavas at the base of the core would be ~400 ka. Still unresolved is the nature and structure of the submarine part of the section (e.g., fragmental pillow vs. coherent lava flows vs. hyaloclastites deposited offshore as a prograding delta). This is potentially a technical as well as a scientific problem

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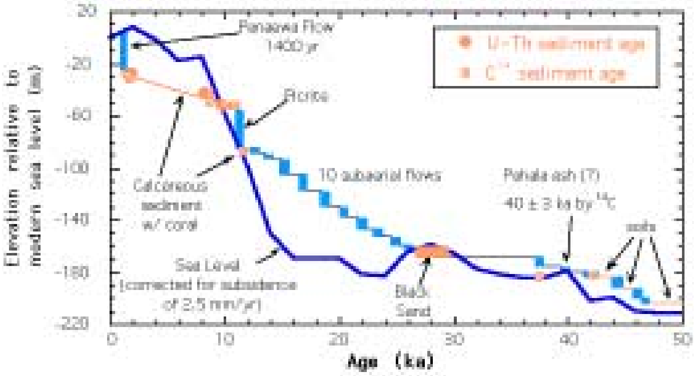

Figure 4. Measured and inferred depth-age relations for the first 200 m of the HSDP pilot hole core. The curve labeled Sea Level represents paleo–sea level in the core and was calculated by using a sea-level curve derived from benthic foraminifera $\delta^{18}O$ values and a subsidence rate of 2.5 mm/yr (Moore et al., 1996). Thick vertical bars indicate actual thicknesses of lava flows. Symbols indicate radiometric age determinations (Beeson et al., 1996; Moore et al., 1996). The only age tie point between 12 and 40 ka is a black sand unit assigned an age of 28 ka on the basis of inferred formation at sea level.

to be addressed by deeper drilling, as conditions may change in the submarine section.

An initial surprise was the importance of sediments in the Mauna Loa section. A thick (>25 m) succession of carbonate sediments rich in coral fragments was encountered immediately below the Panaewa flow. These are interpreted as Hilo Bay lagoonal deposits recording sea-level rise since 10 ka. Dating by ^{14}C and U/Th techniques provides constraints on subsidence of the drill site (by comparison with known sea-level curves) and on dates of the two most recent flows. Other sediments include volcaniclastic units, beach and dune sands, hyaloclastites, and a “bog” deposit. The “bog” deposit (believed to be related to the Pahala ash) is rich in organic carbon and has a ^{14}C age of ~40 ka. Assuming a roughly constant subsidence rate, ages of the sediments deposited at or near sea level can also be estimated from their depth in the core (Fig. 4). A sand layer interpreted as a wind-blown sediment occurs in the Mauna Kea section at a depth of 867 m. Throughout the core, weathered ash deposits are readily recognized as soils.

An important unknown before drilling was the extent of alteration at depth. A factor in choosing the Hilo site was the likely minimal interaction of the lavas with hydrothermal solutions due to distance from rift zones and evidence from water well studies. The possibility had been raised of local intrusions and hot-water flows associated with the nearby Halai Hills and the northeast rift of Mauna Loa. As a whole, the recovered samples are remarkably fresh lavas, although there is some alteration associated with weathering or eruption (e.g., thin iddingsite rims on olivines, oxidized groundmass, low K/P ratios in some lavas) and minor zeolite precipitation is observed in vesicles in the deepest part of the core. The key point is that geochemical and petrological studies have not been compromised by alteration and metasomatism.

Another uncertainty prior to drilling was how to date the core, because important insights into temporal variations in a volcano and connection to mantle processes depend on some fixed time points. The presence of dateable and ancient shoreline sediments in the Mauna Loa section (Fig. 4), giving information on the growth rate of the volcano at the drill site, was fortuitous. As expected, results from Ar-Ar and K-Ar dating of the lavas are mixed (Figs. 2 and 5). Alkalic lavas at the top of the Mauna Kea section have enough K for relatively precise dating. Low-K tholeiites deeper in the Mauna Kea section give less precise ages, but these ages are consistent with gradual slowing of volcano growth toward the end of shield building and with the base of the core being >400 ka. Although the pilot hole did not reach the first major magnetic field reversal (Brunhes-Matuyama boundary at ~790 ka), several polarity excursions were “captured” in the shallower parts of the core. Correspondence of their ages to those of excursions found elsewhere in the world provides a consistency check on ages based on sediment subsidence and radiometric dating of the lavas and sediments.

SCIENTIFIC HIGHLIGHTS FROM THE HSDP PILOT PROJECT

The ultimate goal of the HSDP is a core of several kilometers in the Mauna Kea volcano that can provide information on volcanic evolution that is inaccessible from surface exposures. However, even with a depth of only ~1000 m, the pilot hole significantly extended our knowledge of the evolution of the Mauna Loa and Mauna Kea volcanoes and gave us an indication of the rich insights that can be expected from a deeper hole. The scientific value of the core reflects several factors: (1) The fresh and essentially continuous nature of the core yielded information unavailable from surface reconstructions and disproved some prior expectations. (2) Both the Mauna Loa and Mauna Kea sections in the core spanned gaps between the oldest known subaerially exposed lavas (except a few very old Mauna Loa subaerial lavas along fault scarps) and submarine lavas dredged from the volcano’s submarine rifts and thus filled unsampled parts of these volcanoes’ histories. (3) Perhaps most significantly, the integrated, multidisciplinary approach taken here yielded a more detailed view than had previously been achievable.

Temporal Evolution of the Petrology and Geochemistry of Mauna Kea and Mauna Loa Lavas

Subaerially exposed Mauna Kea lavas are divided into older (70–250 ka), tholeiitic to alkalic basaltic Hamakua Volcanics and younger (4–65 ka), evolved alkalic (hawaiites and mugearites) Laupahoehoe Volcanics (Wolfe et al., 1995). The only other previously sampled Mauna Kea lavas are submarine tholeiites with estimated ages of ~400 ka (Wolfe et al., 1995) dredged from the east rift of Mauna Kea (Frey et al., 1991; Garcia et al., 1989; Yang et al., 1994). Geochemical data place the HSDP Mauna Kea samples on a continuum between the younger Hamakua series and older submarine lavas. Dating puts them in the ~200 ka gap between these groups, making the HSDP pilot hole the longest continuous compositional record for any Hawaiian volcano.

What do we learn from this unprecedented continuous record of Mauna Kea volcanism? The conventional view has been that magmas over most of the history of a Hawaiian volcano are monotonous tholeiitic lavas with alkaline lavas erupting at the start and close of the volcano’s life. Except at the very top of the Mauna Kea section (i.e., <~240 ka), the pilot hole samples are indeed tholeiites, but with significant long-term variations in radiogenic isotope and trace element ratios (Fig. 3). The isotopic variations must reflect changes in source characteristics. Major and trace element variations in the HSDP Mauna Kea tholeiites and the tholeiitic-to-alkalic transition series have been interpreted as a trend with decreasing age toward decreasing extents of melting from garnet-bearing residues at increasing depths of melt segregation (Fig. 3). The trend to decreasing degrees of melting is consistent with progressively decreasing magma fluxes and growth rate of the volcano at the end of shield building (Fig. 5). High-frequency fluctuations superimposed on the long-term compositional trends of the tholeiites provide information on sizes of source heterogeneities. Reversals in some overall isotopic trends and in the trend of decreasing melt fraction with age near the bottom of the core are not understood. All of these variations show that magma

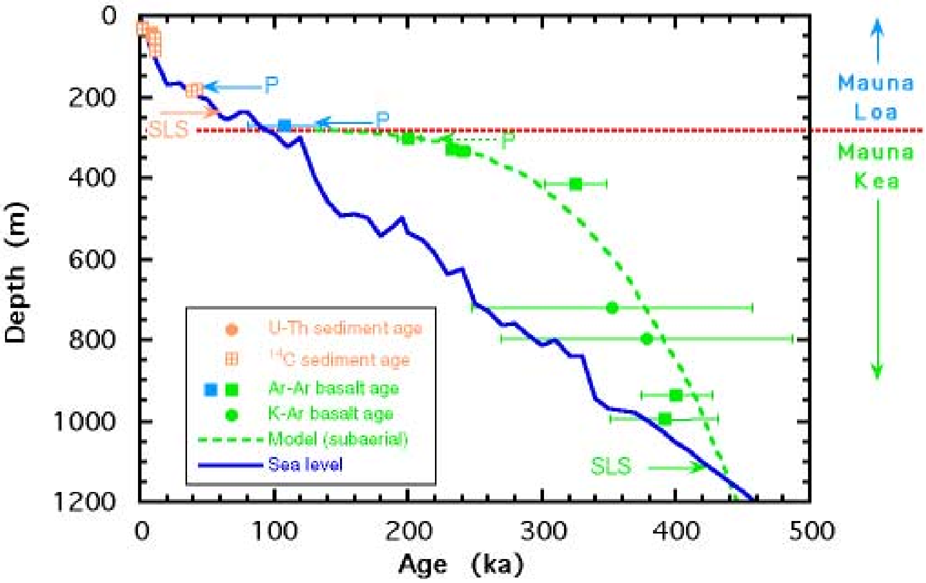

Figure 5. Summary of geochronology of the HSDP core based on radiometric dating (Beeson et al., 1996; Moore et al., 1996; Sharp et al., 1996), paleomagnetism (P) (Holt et al., 1996), and sea-level subsidence (SLS). Right-pointing arrows show minimum ages from the sea-level curve assuming a subsidence rate of 2.4 mm/yr. Left-pointing arrows indicate short magnetic polarity reversals with ages assigned from similar events elsewhere. Also shown are a calculated paleo–sea-level curve (assuming a subsidence rate of 2.5 mm/yr; Lipman and Moore, 1996) and a model depth-age curve for Mauna Kea (dashed-line curve; from DePaolo and Stolper, 1996). The endpoint of the model Mauna Kea curve is set arbitrarily to an age of 130 ka. The Hilo site reached maximum elevation near the end of the tholeiitic part of the shield-building stage (~330 ka). Elevation increased rapidly between 420 and 330 ka as lava accumulation (about 6–7 mm/yr) outpaced subsidence. After 330 ka, lava accumulation was slower than subsidence, and elevation gradually decreased to sea level. Since about 100 ka, Mauna Loa lava accumulation has kept pace with subsidence, and the site has remained close to sea level.

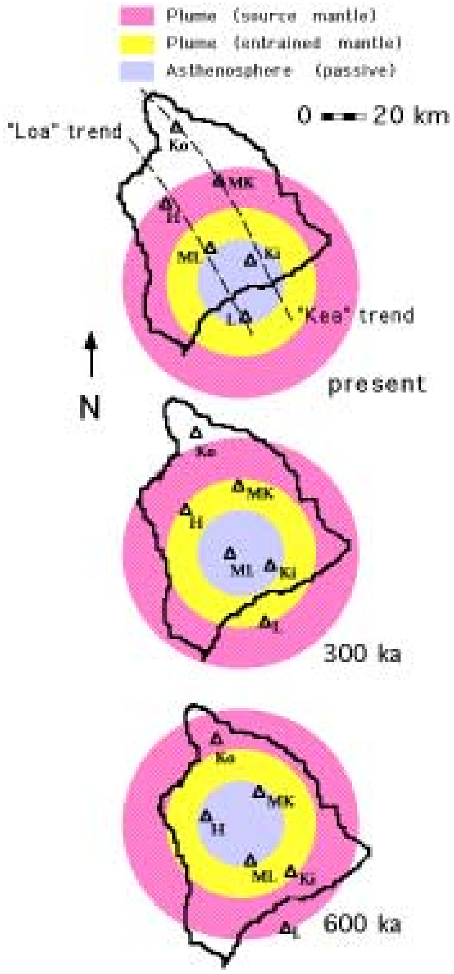

Figure 6. Schematic diagram illustrating northwestward movement (8.6 cm/yr; Clague and Dalrymple, 1987) of Hawaii over a concentrically zoned mantle plume (Hauri et al., 1994, 1996; Lassiter et al., 1996). The plume is envisioned to be heterogeneous due to entrainment of ambient mantle during lower mantle upwelling. Translation of the Pacific plate over the plume leads to progressive sampling of zones. Top: the zero age (i.e., current) configuration—nearly dormant Mauna Kea (MK) is northwest of the plume center, overlying "normal" asthenospheric upper mantle; ML is Mauna Loa, L is Loihi, Ko is Kohala, and Ki is Kilauea. Center: 300 ka (near the middle of the MK section in the HSDP pilot hole)—MK was over the zone of the plume dominated by entrained (lower?) mantle material; Bottom: 600 ka—MK is projected to have been over the central zone of the plume.

sources and genesis were changing as far back as 200 ka in the shield-building phase of Mauna Kea.

Although not as long as the Mauna Kea section, the Mauna Loa section (1.4 to ~100 ka) also fills the temporal gap between exposed subaerial flows and fault scarp and submarine tholeiitic flows thought to be older than 100 ka. As with the Mauna Kea section, chemical and isotopic compositions (Fig. 3) are variable, confirming recent reports of a wider chemical range in Mauna Loa tholeiites than generally appreciated (Garcia et al., 1995; Hauri and Kurz, 1996; Kurz and Kammer, 1991; Kurz et al., 1995; Rhodes and Hart, 1995). For example, variations in incompatible trace element ratios from the base of the section at ~280 m to a core depth of ~200–250 m (corresponding to an age of ~50–80 ka) indicate increasing degrees of melting. An intriguing observation is that like submarine lavas from rift zones in Hawaii (Clague et al., 1995; Garcia et al., 1989, 1995) and in contrast to typical subaerial Hawaiian lavas, picritic lavas (i.e., rich in olivine) are the rule in the core. This could be a local phenomenon due to the hole being low on the volcano flank or a more general phenomenon reflecting high-temperature picritic parental magmas (Clague et al., 1991) and their processing in high-level magma chambers (Garcia et al., 1995; Rhodes, 1995). A final observation is that although the growth rate of Mauna Loa is variable on a 10^4 scale, on a longer time scale magmatic growth appears to be in approximate balance with island subsidence. The observation that Mauna Loa is no longer growing vigorously or even maintaining its size above sea level is consistent with other indications that it is in or nearing its postshield stage.

Mantle Reservoirs and Inferred Plume Structure

Another objective of the HSDP is to obtain an isotopic time series from Mauna Kea lavas. The goal is to set constraints on the nature and temporal variations of the mantle sources of plume lavas in order to deduce the chemical and perhaps physical structure of the intraplate plume source. Previous work on Hawaiian volcanoes has identified several isotopically distinct mantle sources (Chen, 1987; Chen et al., 1991; Stille et al., 1986; Tatsumoto, 1978; West et al., 1987) and has shown that proportions of mantle components change in the postshield and posterosional phases of some volcanoes. These variations are thought to indicate changes in the interaction between the plume and its surroundings. Persistent chemical and isotopic differences between "Loa" trend volcanoes (Loihi, Mauna Loa, Hualalai, etc.) and "Kea" trend volcanoes (Kilauea, Mauna Kea, Kohala, etc.) have also been used to infer plume structure and evolution (Ihinger, 1995; Tatsumoto, 1978).

Isotopic variations in the HSDP tholeiites (Fig. 3) demonstrate long-term changes in source characteristics that precede the prominent change to more alkaline lavas and the decrease in magma flux at the very end of shield building. Pilot project results have been interpreted in terms of a concentrically zoned plume (Fig. 6), in which long-term variability reflects northwestward motion of the vol-

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cano on the Pacific plate over the plume. The concentric plume is envisioned as having a core of material from a deep boundary layer, a ring of entrained lower mantle material, and an outer zone of upper mantle material. With time, the volcano moves over these concentric zones, sampling them in turn. This interpretation can account for long-term differences between “Kea” and “Loa” trend volcanoes, because these volcanoes can be in different positions relative to the concentric zones (see Fig. 6). The shape of the postulated concentric plume is poorly constrained, but this interpretation predicts that as drilling proceeds deeper into the Mauna Kea section, the nature of the sources should change toward the characteristics of the deep plume source in the center of the plume, and that deeper still, the ring of entrained material should again dominate. Although non-unique (alternatives include the “plumelet” hypothesis of Ihinger [1995], a role for the underlying oceanic crust [Eiler et al., 1996], and vertical heterogeneity or shorter length scale heterogeneities [DePaolo, 1996]), this view provides a framework for connecting plume structure and observables in Hawaiian lavas. The old view that the tholeiitic, shield-building phase of a Hawaiian volcano is monotonous and unchanging and that significant variability is confined to the beginning and end of the volcanic life cyle is clearly incorrect.

Growth Rates of Volcanoes

Little is known about the duration of shield building of Hawaiian volcanoes, yet such knowledge is critical for understanding why and how the volcanoes form and are fed. Key observations are that the summits of Hawaiian volcanoes are typically spaced 50 ± 10 km from each other and that Pacific plate velocity is ~10 cm/yr. Some investigators have suggested that the shield-building stages of individual volcanoes are nonoverlapping and that the main phase of growth is ~500 ka (e.g., Moore and Clague, 1992). Others have suggested that the volcanoes overlap significantly and that their active lifetimes could be >1000 ka (e.g., Lipman, 1995; Moore, 1987). The latter is a good reference number, because at a plate velocity of 10 cm/yr, it takes 1000 ka for a volcano summit to traverse a plume of 50 km radius. The pilot hole provides information on the vertical growth rate of Mauna Kea over several hundred thousand years, putting valuable constraints on the time scale of activity.

The expected age vs. depth relation of an idealized Hawaiian volcano has been modeled given simple assumptions about the geometry and subsidence rate of the volcano and about the relation between magma supply and the position of the volcano over the plume. As shown by the dashed curve in Figure 5, this model, which suggests a lifetime for shield building of ~700–800 ka for Mauna Kea, yields an excellent match to actual depth vs. age data for the Mauna Kea pilot hole section. The model also matches constraints on Mauna Kea’s volume, thickness, pre-alkalic summit elevation, and lava accumulation rates. The key point here is that the temporal variability of these parameters is potentially obtainable from an extended time series from a single volcano.

In Figure 5, subaerial lavas plot above the sea-level curve, submarine lava flows plot below it, and sediments and lavas emplaced at sea level plot on it. As expected, on the basis of the discussion above, Mauna Loa points roughly follow the sea-level curve. Mauna Kea lavas are all subaerial, consistent with the core site elevation reaching a maximum of ~400 m above sea level at ~330 ka. According to this analysis, Mauna Kea’s subaerial-submarine transition would have been encountered if the pilot core had gone a few tens of meters deeper.

A growth rate of 2–3 mm/yr and a magma flux of 0.02–0.03 km^3/yr can be derived for the part of Mauna Loa history sampled by the pilot core. These values, results from the Ninole Hills and Kealakekua fault, and results from the Mauna Kea part of the HSDP core suggest that Mauna Kea was at the same stage of evolution from about 400 to 300 ka as Mauna Loa has been from 100 ka to the present. The inferred 300 ka age difference between Mauna Kea and Mauna Loa is consistent with a 10 cm/yr plate velocity and the fact that Mauna Loa is 30 km farther down the plume trace than is Mauna Kea (Fig. 6).

Geomagnetic Results

The HSDP core provides the longest continuous volcanic record of geomagnetic field behavior yet available. These data provide an important complement to records obtained from deep-sea sediments in which field directions are averaged over a few thousand years and may suffer from variable amounts of compaction-induced inclination shallowing. Although the HSDP core is azimuthally unoriented, the high-quality “snapshots” of geomagnetic field intensity and inclination at Hawaii over the past 400 ka have yielded new insights into the global extent of polarity excursions, the relation of excursions to secular variation, the strength of the nondipole field in the central Pacific, and long-term secular variation. The paleointensity signal is still preliminary, but there are patterns that suggest correlations to relative paleointensity records from deep-sea sediments. The inclination record provides evidence for three polarity excursions in the central Pacific. Age constraints from radiometric dating (Fig. 7) enable correlation with excursions elsewhere, supporting the hypothesis that excursions are global events, not localized perturbations of the geomagnetic field. In addition, two of these polarity jumps appear to interrupt briefly long-term changes in inclination (e.g., Fig. 7); i.e., whatever the cause, the field pops back into its long-term state with a considerable “memory.” This suggests that excursions are not merely extreme cases of secular variation, but may result from an independent geodynamo process. Another question that can be addressed with these data is whether the currently weak nondipole field in the central Pacific region extends back through the Brunhes Normal Chron. Comparison of the amplitude of secular variation averaged over the past 400 ka at Hawaii (and hence the strength of the nondipole field) with global paleomagnetic data compilations for the same latitude suggests that the currently weak nondipole field in the central Pacific is not characteristic of most of the time period sampled by the HSDP core. Perhaps the most intriguing result from the HSDP core is the discovery of secular variation periodicities greater than 10 ka. This is considerably longer than typical estimates and has potential implications for geodynamo theory.

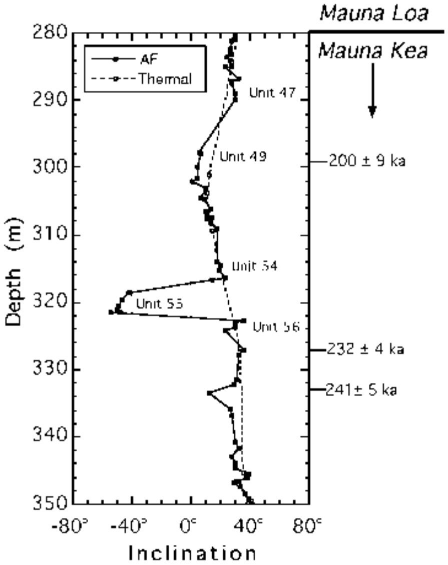

Figure 7. Geomagnetic inclination record for the top (i.e., 280-350 m depth interval) of the Mauna Kea section of the HSDP pilot core (Holt et al., 1996). Unit 55 shows an excursion to reversed inclination; on the basis of Ar-Ar dates (to right, from Sharp et al., 1996) this excursion is correlated with the Jamaica–Pringle Falls events at 200–220 ka.

Downhole Geophysics

Downhole temperature logs show complex profiles (Fig. 8), with several excursions superimposed on a generally negative temperature gradient with depth.

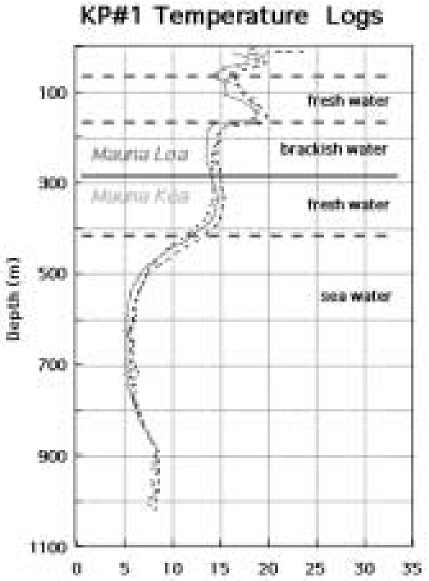

Figure 8. Three downhole temperature logs from an HSDP pilot hole taken between December 1993 (just after completion of drilling) and May 1995 (Thomas et al., 1996). Note the overall decrease in temperature with increasing depth, which contributed to the unaltered nature of the core. Ground-water zones (two freshwater, two saline) were identified by chemical and isotopic analysis of water samples and downhole logging (Paillet and Thomas, 1996; Thomas et al., 1996). The freshwater zone underlying the Mauna Loa–Mauna Kea boundary appears to be derived from high on the slopes of Mauna Kea. The deeper sea-water zone appears to be derived from direct, horizontal input from the ocean and is little changed by interaction with the volcanic pile.

The minimum temperature is about 5° C at a depth of 600 m. The similarity of the temperatures in the core hole to the ocean thermocline confirms the absence of hydrothermal activity and demonstrates the efficiency of ocean water circulation through rock units beneath the drill site. Temperature excursions at shallower depths (e.g., 70 m and 350 m; Fig. 8) suggest that water from several sources is passing through a series of vertically isolated subsurface aquifers underlying this site.

Borehole televiewer analysis of the strike and dip of downhole fractures indicates that the distribution of fracture orientations has changed with time. Because most of the fractures are inferred to be associated with tensional cracking during cooling of the lava flows, the observed change in orientations is interpreted as reflecting the evolution of surface slope angles during the growth of the Mauna Kea and Mauna Loa shields.

Ground-water Hydrology

Hydrological and water chemistry studies on the well after completion of drilling show a complex hydrological system beneath this site. Pumping drawdown and tidal flux measurements in the well prior to perforation show that compaction has not substantially changed aquifer permeability of deep (>700 m) units. These deep units contain relatively young saline water (~3.6–5.6 ka) only minimally changed in chemical composition from sea water by interaction with the basalts. The young age of this cool water demonstrates rapid circulation of sea water through the volcano at depths of ~1 km even in the absence of hydrothermal temperatures. Fluid at ~325 m is fresh water that the induction logs indicate is a thick zone with saline water above and below (Fig. 8). Its location below the soil layer at the Mauna Loa–Mauna Kea contact suggests that this is fresh recharge from Mauna Kea flowing beneath a barrier formed by this soil. Isotopic analysis of this water shows that it was derived from an average elevation of ~1800 m and has a maximum age of ~2.8 ka. This fresh water may be channeled beneath the overlying sea water–saturated Mauna Loa basalts and ultimately discharged by deep offshore submarine springs. There is also evidence for fresh water in a second, shallower zone in the Mauna Loa section (Fig. 8). The picture that emerges at the HSDP site of alternating intervals of fresh and salt water saturation in the nearshore environment and of freshwater transport beneath saline water contrasts with widely applied models of Hawaii's hydrology, which have changed little since they were introduced by Stearns and Macdonald (1946).

PROSPECTS FOR DEEPER SCIENTIFIC DRILLING IN HAWAII

The results of the ~1 km HSDP pilot project demonstrate that important issues in mantle geochemistry and geodynamics, volcanology, and paleomagnetism can be addressed in a unique and powerful way by drilling in Hawaii. Many of these issues cannot be adequately addressed in the absence of drilling. The experience from the 1993 HSDP pilot hole provides a solid basis for planning and implementing a more ambitious deeper drilling project in Hawaii. As an outgrowth of the pilot program, the National Science Foundation Continental Dynamics Program has recently recommended funding a program to extend the HSDP to greater depth. The current plan is to: (1) drill continuously ~4.5 km into the flank of the Mauna Kea volcano in the vicinity of Hilo; (2) perform a suite of downhole logs and experiments to characterize the hole; and (3) describe and analyze the recovered samples with a wide array of techniques. Extrapolation of pilot project results suggests that the age at the base of the proposed core will be 650 ± 100 ka. As with the pilot project, the major focus will be to recover and characterize a continuous sequence of samples that when properly logged and curated will serve as a valuable resource for future generations.

The drilling and scientific plans as currently envisioned consist of several phases. The site selection phase has already begun by evaluating several sites in the vicinity of Hilo. The tentative drilling program consists of three phases of continuous wire-line coring with target depths for Phase I of ~1700 m, Phase II of ~3400 m, and Phase III of ~4500 m. Each phase is expected to span two years, with about 6 months devoted to drilling and coring and the rest spent on downhole research and analyses of samples. The downhole logging program will be conducted at intervals through each drilling phase. After setting and cementing of the casing in the hole at the end of each phase, vertical seismic profile surveys will be conducted. This will be followed by perforation of the casing and sampling and analysis of fluids, as well as hydrologic analyses of the units. The syn- and postdrilling analytical program for each stage will be modeled after that in the pilot hole project, and will consist of modern geochemical, petrological, geochronological, and geomagnetic characterization of the recovered core. Core characterization will provide the basis for addressing issues in mantle structure and processes, volcano structure and evolution, and detailed tracking of the magnetic field, and it will guide future investigators in their use of this unique record of the history of a major oceanic volcano.

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WASHINGTON REPORT

Bruce F. Molnia

Washington Report provides the GSA membership with a window on the activities of the federal agencies, Congress and the legislative process, and international interactions that could impact the geoscience community. In future issues, Washington Report will present summaries of agency and interagency programs, track legislation, and present insights into Washington, D.C., geopolitics as they pertain to the geosciences.

Science and Technology and the Future of Cities

> ***The fact is that science and technology have a crucial role and responsibility in providing solutions and in ensuring the long-term sustainability of cities.***
>
> **— Nobel laureate F. Sherwood Rowland,**
> **Foreign Secretary to the U.S. National Academy of Sciences**

> ***Neither the pace of scientific research nor its transfer into practical application has kept up with the rapidity of urban growth, especially in developing countries.***
>
> **— P. N. Tandon, former president of the**
> **Indian National Science Academy**

Information released by the National Academy of Sciences (NAS) describes that on May 31, in Istanbul, Turkey, 72 of the world's academies of sciences issued a statement urging world leaders to raise to a higher priority the role of science and technology in solving urban problems. A related statement issued by 14 engineering academies also underscores the role that the world's engineering community should play in helping to resolve the seemingly inherent conflicts that surround the simultaneous pursuit of economic advancement and environmentally sustainable development. On June 6, both statements were officially transmitted to delegates of the United Nations Conference on Human Settlements, for their consideration. "The potential for science and technology to ameliorate or

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