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Introduction to special section: Hawaii Scientific Drilling Project

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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, but the origin of these volcanoes is not explained by the plate tectonic paradigm [*Engebretson et al.*, 1985; *Molnar and Stock*, 1987; *Morgan*, 1971, 1981, 1983; *Wilson*, 1963]. The most widely held view is that these chains of volcanoes form from magma generated by decompression melting of localized, buoyant upwellings in the mantle [*Ribe and Christensen*, 1994; *Richards et al.*, 1988; *Sleep*, 1990; *Watson and McKenzie*, 1991]. These upwellings, or "plumes," are believed to originate at boundary layers in the mantle (e.g., at the core-mantle boundary or near the boundary at ~670 km between the upper and lower mantle), and the cause of the buoyancy may be both compositional and thermal [*Campbell and Griffiths*, 1990; *Griffiths*, 1986; *Richards et al.*, 1988; *Watson and McKenzie*, 1991]. Mantle plumes are responsible for about 10% of the Earth's heat loss and constitute an important mechanism for cycling mass from the deep mantle to the Earth's surface. Studies of the chemical and isotopic compositions of lavas from intraplate volcanoes, especially ocean island volcanoes, have contributed significantly to our knowledge of magma genesis in the mantle [*Carmichael et al.*, 1974; *Macdonald et al.*, 1983] and the compositional heterogeneity of the mantle [*Allègre et al.*, 1983; *Hart*, 1988; *Hart et al.*, 1986; *Kurz et al.*, 1983]. Of particular importance is the identification of distinct compositional end members in the mantle, the origin and distribution of which provide insight into the long-term differentiation of the mantle-crust system, the recycling of oceanic crust and continental sediment into the mantle, and the history of the lithosphere [*Allègre et al.*, 1995; *Farley et al.*, 1992; *Hart*, 1988; *Hofmann and White*, 1982; *McKenzie and O'Nions*, 1983; *Weaver*, 1991; *Zindler and Hart*, 1986].

A fundamental limitation in the study of hot spot volcanoes is that the major volume of each volcano is inaccessible to sampling and is consequently unknown. Erosion typically exposes only hundreds of meters of an oceanic volcano's interior, out of a total thickness of 6 to 20 km, because rapid subsidence after extinction preempts erosional downcutting. For example, the Hawaiian-Emperor chain has been active for at least 70 Myr, but all we can generally examine for any individual Hawaiian volcano is that small fraction of its history (typically, the final 5-10%) that is exposed subaerially. Thus, although each Hawaiian volcano acts as a probe, sampling the plume output as the Pacific plate carries the volcano over the hot spot and recording this output in stratigraphic succession in its lavas, the long-term evolution of any individual volcano during its ~1 Myr passage across the plume is almost entirely inaccessible. Continuous core drilling through a sequence of lavas on the flank of an oceanic volcano is probably the only way to obtain a stratigraphic sequence representing the complete traverse of the plume. If an extended part of such a succession of lava flows could be sampled by drilling and then analyzed, it would provide critical information on mantle plume structure and origin.

In recognition of the essentially unique research 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 drill continuously to a depth of several kilometers in the flank of the Mauna Kea volcano [*DePaolo et al.*, 1991]. Hawaii was a natural target since as the best studied volcanic construct on Earth, it is the archetype of ocean island volcanism and provides the best possible scientific framework for a major project of this sort.

This special section of the *Journal of Geophysical Research* reports the results of initial scientific characterization of the 1056-m-deep core hole drilled in 1993 as the first phase of the HSDP. This goal of this introduction is to describe the project and to provide context for the diverse set of scientific studies reported in the following papers.

Hawaii Scientific Drilling Project

Core drilling of a "pilot hole" (named Kahi Puka 1, or KP-1), funded by the National Science Foundation Continental Dynamics Program, took place in Hilo, Hawaii, from October to December 1993 and was done by Tonto Drilling Services, Inc. (Salt Lake City, Utah). The following 18 months were devoted to petrological, geochemical, geomagnetic, and volcanological characterization of the recovered core, downhole logging, and the fluid sampling program. The primary scien-

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tific objectives of the pilot hole stage of the project were essentially those of the larger project, to characterize the petrology, geochemistry, and rock magnetism of a nearly continuous sequence of Hawaiian lavas erupted over a long time period. Other objectives of the pilot project were demonstration of the technical feasibility of the drilling program and of the ability of the diverse group of scientists involved in the project (covering many disciplines, institutions, and countries) to work together effectively.

The HSDP pilot hole drill site was near Hilo Bay on the surface of the ~1400-year-old Panaewa flow series from the Mauna Loa volcano (Figure 1). This particular site was chosen because (1) it is far from magmatic rift zones and from the summits of Mauna Loa and Mauna Kea, thereby minimizing the chances of encountering intrusives, alteration, and high temperature fluids during drilling; (2) its proximity to the coastline maximized the probabilities of encountering submarine flow units and relatively old lavas in a shallow hole; and (3) drilling began in recent lavas erupted from the Mauna Loa volcano but at depth penetrated underlying lavas erupted from Mauna Kea, which allowed us to test our ability to distinguish between lavas from different volcanoes. Other factors leading to this site were related to permitting, including appropriate zoning and land use designation as well as an ability to screen the drilling activities from a nearby residential community.

The drilling lasted 46 days; the total depth achieved was 1056 m with an average penetration rate >20 m/d. The average penetration rate during periods of drilling (excluding time for logging, waiting on cement, rig repairs, etc.) was ~30 m/d. By comparison, average penetration rates from previous core drilling on the Kilauea East Rift Zone ranged from less than 10 m/d to about 22 m/d for coring time only (H. Olson, unpublished data, 1991). Core recovery for the entire drill hole averaged about 90%, with the major loss zones being in unconsolidated sediments, which were not effectively captured by the core barrel, and in zones of rubble, which jammed the core barrel.

One of the key goals while the drilling was progressing was to process each segment of the core within 24-48 hours after recovery. A successful procedure was developed that built on experience from the Cajon Pass and Creede drilling projects. The detailed core handling and logging procedures are presented along with the core logs and photographs of the entire core in a separate volume [*Hawaii Scientific Drilling Project*, 1994]; the logs and photographs are also available on the Internet (at http://expet.gps.caltech.edu/Hawaii_project.html). The core was divided into a working split (currently stored at the California Institute of Technology) from which all samples have so far been taken and an archival split (curated by the U.S. Geological Survey Core Research Center in Denver). A set of reference samples for geochemical analysis was collected from the core (only from interior sections of the core, avoiding the parts of the core that were in contact with the bit or the core barrel) in conjunction with the logging program. These were prepared (crushed and cleaned) according to a common procedure at the Massachusetts Institute of Technology and the University of Massachusetts, Amherst, and then distributed to the various investigators for analysis. Thin sections were prepared from samples adjacent to the parts of the core from which the powders for geochemical analysis were prepared. In addition to the reference suite, many other samples were later taken from the working split, including all the samples used in the geomagnetic investigations and samples other than the reference suite that were analyzed geochemically.

Description of the Stratigraphic Section

The core logging led to the designation of 227 units (numbered in stratigraphic succession, from the top to the bottom of the core), out of which 208 are lava flows; the remainder are ash beds, marine and beach sediments, and soils. A generalized, composite lithologic section is shown in Plate 1. A more detailed column is available on the Internet at http://expet.gps.caltech.edu/Hawaii_project.html.

Units 1-43 are interpreted to be part of the Mauna Loa volcano; units 44-227 have been assigned to the underlying Mauna Kea volcano. The contact between these volcanoes at a depth of 279.5 m is unambiguous and sharp. Abrupt changes are observed in trace element ratios [*Hofmann and Jochum*, this issue; *Rhodes*, this issue] and He, O, Sr, Pb, and Nd isotopic ratios [*Eiler et al.*, this issue; *Hauri et al.*, this issue; *Kurz et al.*, this issue; *Lassiter et al.*, this issue]. Other observations strongly support this identification of the boundary between lavas from the two volcanoes: (1) the projection of the exposed slope of Mauna Kea under the drilling site is precisely at this depth; (2) lava flows from shallower than 280 m are interlayered with near-shore sediments and are systematically thicker than those from deeper levels (Plate 1) (G.P.L. Walker, written communication, 1995), consistent with expected differences between Mauna Loa lavas erupted as gently sloping lava deltas extending into Hilo Bay and Mauna Kea lavas erupted on steep slopes well above sea level [*DePaolo and Stolper*, this issue; *Lipman and Moore*, this issue; G.P.L. Walker, written communication, 1995]; (3) a significant soil horizon is present at the geochemically defined boundary; (4) the intercalation of alkalic and tholeiitic lavas in the 50 m below the geochemically defined disconformity is consistent with the end of shield building of Mauna Kea [*Rhodes*, this issue]; and (5) the major element compositions of the tholeiites above and below the chosen contact, although not definitive, are consistent with known differences between lavas from Mauna Loa and Mauna Kea [*Rhodes*, this issue].

Weathered ash deposits are readily recognized as soils throughout the core. Near-shore sediments are interspersed with lava flows in the Mauna Loa part of the section, indicating that the drill site was close to the shore during this time period and therefore that aggradation due to lava flows and subsidence were roughly in balance. A succession (~25 m) of carbonate sediments rich in coral fragments was encountered immediately below the Panaewa lava flow at the surface. These sediments are interpreted as Hilo Bay lagoonal deposits that record the rise of sea level since 10 kyr ago. Other sediments include volcaniclastic sediments, beach and dune sands, hyaloclastites, and a "bog" deposit rich in organic carbon. Only one sand, interpreted as a wind-blown sediment, is present in the Mauna Kea part of the section (at a depth of 867 m).

No intrusive units have been identified. Nearly all of the sampled lavas are subaerial (as opposed to submarine). That subaerial lavas are found more than a kilometer below current sea level is not surprising because Hawaii is known to be subsiding at a rate of 2.0-2.5 mm/yr [*Moore*, 1987; *Moore et al.*, this issue]. The minimum age of the lavas at the base of the core is thus estimated to be ~400 kyr, since this is how long it would take lava erupted at sea level to subside to this depth at a rate of 2.5 mm/yr.

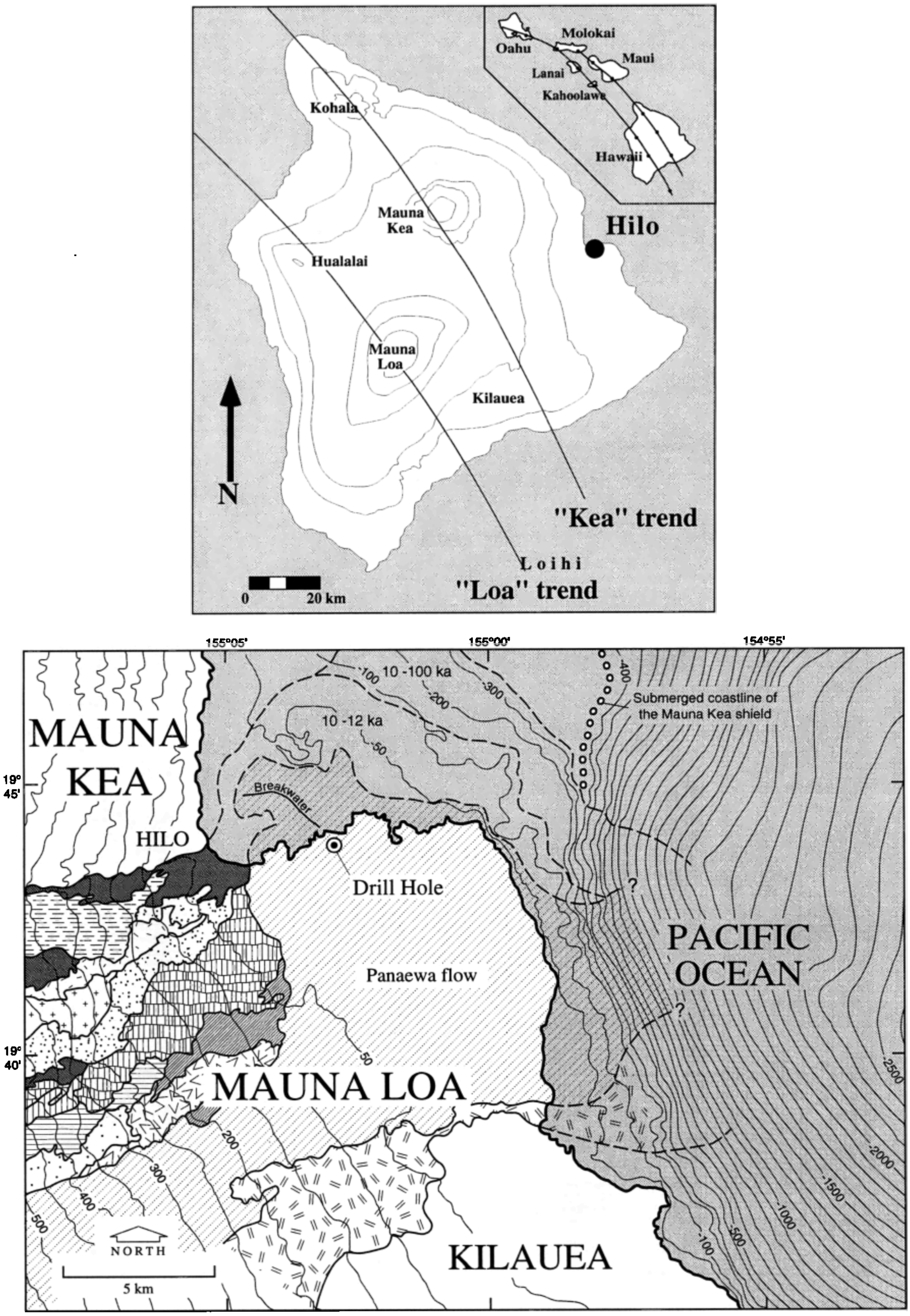

Figure 1. Location maps for the Hawaii Scientific Drilling Project. (top) The Hawaiian Islands (inset) and the island of Hawaii, showing the "Loa" and "Kea" trends, the volcanoes on the island of Hawaii (including Loihi), and the location of the HSDP pilot hole at Hilo. (bottom) Detailed geologic map of the vicinity of Hilo and the location of the pilot hole. Volcano names indicate the source of the surface flows. After *Lipman and Moore* [this issue].

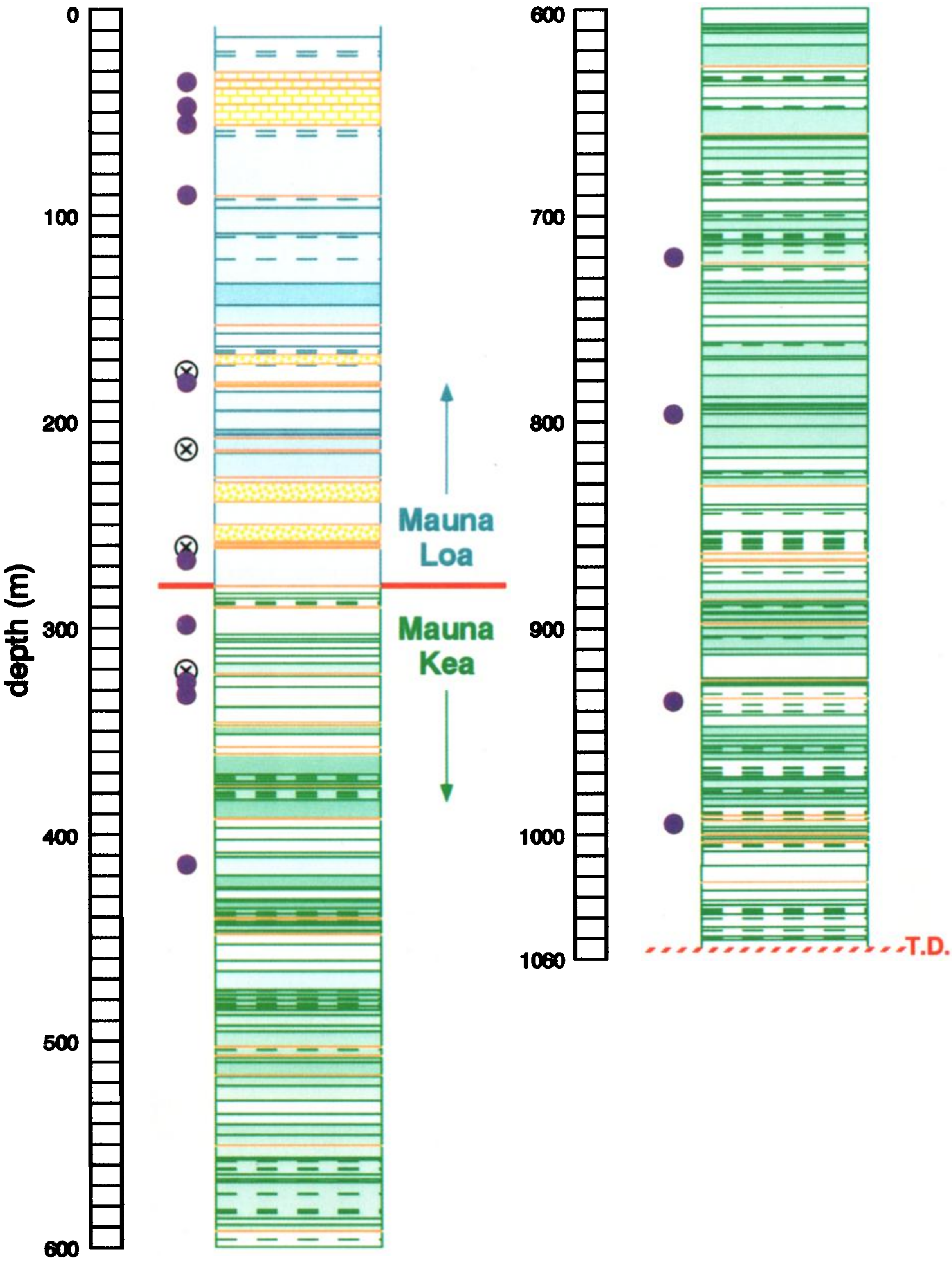

Plate 1. Simplified lithologic column of the HSDP pilot core. Blue and green indicate Mauna Loa and Mauna Kea basaltic lava flows, respectively. Note the greater thickness of flows in Mauna Loa part of the section relative to the Mauna Kea part. The intensity of the shading is proportional to the phenocryst content. Dashed lines are internal flow units. Orange indicates sedimentary units. All but one of the sedimentary units in the Mauna Kea part of the section are thin soils or ash beds. Sediments in the Mauna Loa part of the section also include soils and ash beds but are primarily clastic carbonates, beach sands, or hyaloclastites. Depths at which radiometric ages are available are indicated by a solid circle adjacent to the section [*Beeson et al.*, this issue; *Moore et al.*, this issue; *Sharp et al.*, this issue]. Depths of excursions in the geomagnetic field [*Holt et al.*, this issue] are indicated by a circled cross adjacent to the section.

In choosing the Hilo area for the site, one factor was the expectation that there would be minimal interaction of the section with hydrothermal solutions, based on distance from rift zones and previous studies of well waters. The overall impression of the recovered samples is of remarkably fresh lava, although there is some alteration associated with weathering or with eruptive conditions (e.g., thin iddingsite rims on olivines, oxidized groundmass, low K/P ratios in some lavas). The key point is that geochemical and petrological studies have not been compromised by alteration and metasomatism. In the deepest part of the core, minor zeolite precipitation is observed.

Samples in the following articles are identified either by their unit numbers, the "core run number" (i.e., each cored interval was given a number, R1 to R467, where lower numbers refer to sections of core recovered earlier in the drilling), the position of the top of the sample (in feet) relative to the top of an individual core run (e.g., R303-1.85A refers to a sample from core run 303, where the top of the sample was 1.85 feet (1 foot = 0.3048 m) from the top of the core run; letters such as the "A" are used when several samples were taken from the same depth), or the depth in meters relative to the rotary table on the drill rig (unless otherwise indicate). Details of these various designations are explained in the core log volume [*Hawaii Scientific Drilling Project*, 1994]. The rotary table on the drill rig was 4.22 m above sea level, so if depths relative to sea level are required, 4.22 m must be subtracted from the reported depth.

Value of the HSDP core

The articles included in this special section provide a wide-ranging view of the evolution of Hawaiian volcanoes and demonstrate how much can be learned about mantle and higher level magmatic processes and volcano evolution from a long, continuous sequence of lavas when it is systematically examined with the full range of modern analytical techniques. Moreover, when properly logged and curated, such a suite of rocks can serve as a valuable resource for future generations. The particular value of the HSDP core relates to several factors: (1) The essentially continuous nature of the core, which was also typically very fresh, yields information unavailable from reconstructions based on surface exposures. (2) For both the Mauna Loa and Mauna Kea sections of the core, the recovered samples fill in previously unsampled parts of the volcano's history; i.e., for each volcano, the sampled lavas span the gap between the oldest known subaerially exposed lavas (excepting a few very old subaerial lavas from Mauna Loa exhumed along fault scarps) and the limited sampling of older submarine lavas dredged from the volcano's submarine rifts. Thus these samples represent the longest nearly continuous, detailed record of the history of Hawaiian volcanoes. (3) Perhaps most significantly, the integrated, multidisciplinary approach taken here yields a more detailed view than had previously been achievable.

Among the topics covered in this special section are the following: (1) the temporal evolution of the petrology and geochemistry of Mauna Kea and Mauna Loa lavas and sources and their correlations with magma flux, source depth, and the stage of shield building; (2) the long-term variability of stable and radiogenic isotope ratios of Mauna Kea and Mauna Loa volcanoes, and their relation to the structure and compositional variations of mantle plumes; (3) the growth and subsidence rates of volcanoes during shield building and their relations to magma composition and isotopic ratios, to the total duration of shield building in Hawaiian volcanoes, and to the expected rates for even earlier stages of shield building of Hawaiian volcanoes; (4) the ages and nature of short-duration geomagnetic polarity events in the first half of the Brunhes Normal Chron and long-term patterns in paleointensity of the local magnetic field; and (5) downhole geophysical observations (e.g., temperature, resistivity, fracture orientation) and the relations between groundwater hydrology (e.g., the age, composition, source, and flow of water) and volcano structure.

In our view, the papers presented here demonstrate that critical issues in mantle geochemistry and geodynamics, volcanology, and paleomagnetism can be addressed in a unique and powerful way by drilling in Hawaii and that these issues cannot be adequately addressed in the absence of drilling. On this basis we suggest that even deeper drilling to sample continuously the long-term history and deep structure of Hawaiian volcanoes can present extraordinary opportunities for increased understanding of hot spot volcanism and magma generation. Moreover, the availability of core from such drilling would provide sample suites of lasting value to future generations of scientists.

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