



Fume cloud produced by eruption of Puu Oo, Kilauea east rift zone, as seen from Hawaiian Volcano Observatory. View is toward east, across Kilauea caldera, on October 21, 1985. Photograph by J.D. Griggs.

## PETROGENESIS AND VOLCANIC GASES

Petrologic and geochemical studies come alive in Hawaii because such processes as igneous differentiation and exsolution of volatile species in magma can be studied as they happen. Many igneous processes can in fact be quantitatively understood only through direct observation of igneous events. Such events, accurately delineated in time and space in turn, constrain deeper processes related to the construction of Hawaiian volcanoes. The first chapter in this section gives an overview of what we have learned about the petrogenesis of Hawaiian volcanoes, with an emphasis on the contributions made by studies of active volcanism.

The second and third chapters provide petrologic observations on recent volcanic activity; chapter 25, combined with chapter 48 in the section on dynamics, provides fascinating insights into one of Kilauea's most famous eruptions, the 1959 eruption in Kilauea Iki Crater. Chapters 26 and 27 address one of the most fundamental problems of Hawaiian petrology—the characterization of mantle sources for Hawaiian magma.

Chapters 28 through 34 treat comprehensively the study of volatile species associated with active Hawaiian volcanism, including a report on the first systematic collection of gases during an eruption of Mauna Loa. Chapter 34 outlines a new technique for rapid transmission of data from gas monitoring. The section closes with an interdisciplinary study of elemental mercury, tracing its path from volcanic emanations, through concentration in plants, to possible effects on human health.



Rainbow Men  
Hawaiian Petroglyph  
Nuuanu, Oahu

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## RECENT ADVANCES IN HAWAIIAN PETROLOGY AND GEOCHEMISTRY

By Thomas L. Wright and Rosalind T. Helz

### ABSTRACT

Hawaiian petrology continues to be a subject of great scientific interest. Several developments over the last three decades have substantially increased our knowledge of the processes by which basaltic magma is generated in the mantle, transported to storage in the crust, and erupted onto the surface. Significant areas of study include the following:

(1) Active volcanism at Kilauea Volcano, including the study of lava lakes ponded in pit craters. Lava lakes have provided natural laboratories in which numerous petrologic processes associated with cooling, crystallization, and differentiation of basaltic magma have been quantified. The detailed study of Kilauea lava chemistry in time and space has resulted in recognition of other petrologic processes, including storage of chemically distinct mantle-derived magma batches and mixing of these parental magma batches with magma stored and fractionated in the rift zones. Geodetic and seismologic studies at Kilauea have been critical in establishing a context in which the petrologic data can be evaluated. One unsolved question is the source of magma for each active volcano. Seismic evidence suggests a common staging area at 40 km depth, whereas petrologic studies show that each active volcano has unique chemical characteristics, indicating isolated storage regions.

(2) Detailed study of the recently discovered Loihi Seamount, the newest volcano in the Hawaiian Chain, has revealed a preshield alkalic stage similar, but not identical, to the postshield alkalic stages on the subaerial volcanoes.

(3) Detailed stratigraphic studies of individual volcanoes, using major element chemistry, trace-element chemistry, and radioactive-isotope systems, show diversity of chemical evolution in each volcano in the chain, particularly within the alkalic stage that follows construction of a tholeiitic shield. There is also diversity in the chemical and isotopic relations linking shield lava to postshield lava. The combined isotopic and chemical data has revealed significant complexity in the source mantle for Hawaiian lava, both within the stratigraphic record of a single volcano and among different volcanoes.

(4) The origin of Hawaiian magma, as defined by depth and degree of partial melting, enriched versus depleted sources, and mineralogy of the source mantle, is unresolved at present. The increasing amount of data indicates a need for more definition of the structure and composition of the Earth's mantle from such diverse disciplines as seismic tomography and the experimental physics of melting and melt transport.

Finally, all models that address the origin of the Hawaiian Islands, whether geochemical or geophysical, need to take into account the constraints imposed by seismic, geodetic, and petrologic studies of the active volcanoes in the chain.

### INTRODUCTION

The Hawaiian Islands occupy a unique place in igneous petrology. Early in the development of the science Hawaii was

recognized as a locale of petrologic significance, partly because of its active and approachable volcanoes, partly because of its location in the middle of the Pacific Ocean—uncomplicated by the presence of other kinds of terrain—and finally because of the wide variety of volcanic rock types available for study. Long before the recognition of plate tectonics, the Hawaiian Islands were recognized from the degree of erosion and the location of volcanic activity as having formed in an orderly progression from northwest to southeast. J.D. Dana saw that the islands were distributed in a way that defined parallel, but offset, segments that he related to tectonic controls (see Clague and Dalrymple, chapter 1, part I). Early visitors to Kilauea outlined in vivid descriptions the general nature of Hawaiian eruptions, and early visits to the bubbling lava at Halemaumau resulted in gas collections that still rank among the best ever obtained from an active volcano (Greenland, chapter 28).

With the advent of plate tectonics, the Hawaiian Chain became a classic example of midplate volcanism. The orderly progression of volcanism was quantified by radiometric dating, and the historical development was extended by recognition that the chain continued to the northwest past Midway Island, defined by long submerged seamounts of the Emperor Chain (see Clague and Dalrymple, chapter 1, part I). These seamounts were also sampled as part of the Deep Sea Drilling Project, and subsequent study revealed a remarkable uniformity, starting about 70 Ma, of both the rate of progression of volcanism and of the products of volcanism. For example, tholeiitic basalt from the 69-Ma Suiko Seamount (Clague and Dalrymple, chapter 1, part I) is geochemically similar to basalt presently being erupted at Kilauea and Mauna Loa (Clague and Frey, 1980; Kirkpatrick and others, 1980).

Earlier land-based studies by numerous workers, notably H.S. Stearns and G.A. Macdonald, had identified a sequence of compositional changes in the building of Hawaiian volcanoes that appeared to be the same, although not always complete, in each studied volcano (Clague and Dalrymple, chapter 1, part I; Macdonald and others, 1983). From these studies each Hawaiian volcano was inferred to pass through the following stages: (1) An early and voluminous tholeiitic stage that constructed huge shields rising from the ocean floor, exemplified by the active volcano Mauna Loa; (2) a period of much less voluminous alkalic volcanism, forming a small cap of mildly undersaturated alkalic lava on the tholeiitic shield, for example, the younger lava of Mauna Kea; (3) a period of erosion, which has been determined to be 0.5–2 m.y. long, in which the volcanic mass above sea level was thoroughly dissected; and (4) a period of basanitic or nephelinitic volcanism following the erosion of the old shield. The famous Oahu landmark Diamond Head is the product of eruption in this last period. This framework has been

modified as more volcanoes have been sampled and studied in detail. For example, work on Loihi Seamount has identified a preshield alkalic stage (Clague, in press). In no single volcano are all stages fully represented. Nephelinitic volcanism is rare, but well-developed series are presented on Kauai (Koloa Volcanics) and in the Koolau Range on Oahu (Honolulu Volcanics). The Kiekie Basalt on Niihau (which includes Lehua Island, Macdonald and others, 1983) and some of the Leeward Islands (Kaula, Macdonald and others, 1983) may include nephelinitic rocks. The latest, most undersaturated rocks to the southeast are not separated from the earlier alkalic series by nearly as long an interval of erosion (<500,000 years versus 2 m.y. for Kauai and Oahu) and are basanites, not nephelinites. The volcanoes that have a nephelinitic series show very little development of an earlier mildly alkalic series, whereas the basanites (the Lahaina Volcanics on West Maui Volcano, the Hana Volcanics on Haleakala Volcano) tend to overlie a lower, more mildly alkalic series. In this paper we will use the terms "nephelinitic series" to describe the truly posterosional rocks, bearing in mind that these rocks range in composition from alkali basalt through true nephelinites, and "upper alkalic series" for the rocks of other volcanoes that show a lesser erosional break.

The older Hawaiian volcanoes can be subdivided into groups on the basis of variations in the character of the mildly alkalic rock series present. This subdividing was first done by Macdonald and Katsura (1964), who recognized a Haleakala type and Kohala type. Further study suggests four significant variants:

(1) Haleakala type: characterized by a thick, transitional zone of interbedded tholeiite, transitional basalt, and ankaramite overlain by hawaiite and mugearite. Most analyzed alkali basalt in this type is slightly hypersthene-normative. Other volcanoes of this type are Mauna Kea (Macdonald and Katsura, 1964) and East Molokai (Beeson, 1976).

(2) Kohala type: mafic alkalic rocks are subordinate. The dominant rock types are hawaiite and mugearite, which form a thin cap of lava that was erupted from vents scattered around the tholeiitic shield. Trachyte may be present. As in the first type, alkali basalt in these alkalic series is slightly hypersthene-normative. Other examples are Waianae, West Molokai, and West Maui (Macdonald and Katsura, 1964).

(3) Hualalai type: characterized by an almost bimodal suite of nepheline-normative alkali basalt and trachyte (Macdonald, 1968; Clague and others, 1980). No other representatives of this type are known.

(4) Koolau type: mildly alkalic series is either absent, or present only as a few flows at the top of the tholeiitic sequence. Other examples are Lanai (Bonhommet and others, 1977), Kauai, Niihau, and Kahoolawe (Macdonald and others, 1983).

The distribution of these various types of Hawaiian volcanoes is not random. All the volcanoes are distributed on several locus lines (fig. 23.1). Two locus lines are defined for the southeastern islands of the Hawaiian Chain: the Loa line, passing through Mauna Loa, and the Kea line, passing through Mauna Kea (fig. 23.1). When looking at figure 23.1 with the above classification in mind, two features stand out. First, adjacent volcanoes are almost always of different types. Second, some types occur *only* on the Loa or Kea

locus. For example, the Haleakala type is found only on the Kea locus, and the Koolau type only on the Loa locus. The existence of the four subtypes suggests that the groups result from significant differences in either source or plumbing, or both. The observations on the spatial array further suggest that adjacent volcano sources interact in some fashion at this stage in the volcano's development and that consistent differences in source may exist between the Loa and Kea locus lines. The latter possibility is supported by the trace-element data of Budahn and Schmitt (1985) on tholeiitic basalt from the Hawaiian volcanoes. Also, some correlation may exist between these four types and the nature of the various later alkalic rock series. In particular, the nephelinitic series has so far been observed only on Koolau-type volcanoes, found on the Loa locus. A more thorough examination of the upper alkalic series, seen mostly on Haleakala- and Kohala-type volcanoes on the Kea locus, may reveal other differences between the various late alkalic series that correlate either with volcano type or location.

In the last two decades, our understanding of Hawaiian volcanism has been greatly expanded as a result of the following important studies: (1) Detailed seismic, geodetic, and petrologic studies of Kilauea, conducted at the Hawaiian Volcano Observatory, have provided quantitative data on the processes of cooling, crystallization, and differentiation of tholeiitic basalt, and an understanding of how tholeiitic magma is transported and stored during construction of an Hawaiian shield; (2) the discovery, first by bathymetry, and secondly by seismic swarms and dredging, of an active undersea Hawaiian volcano—the Loihi Seamount—confirmed the continued southeastward progression of Hawaiian volcanism and, more importantly, overturned ideas about the uniformity of the tholeiitic stage of volcanism; (3) modern petrologic and geochemical studies of volcanoes in the Hawaiian Chain in all stages of development have been definitive in establishing the nature of oceanic midplate volcanism and the complexities that can occur in even this most simple of geologic settings; and (4) the study of xenoliths, high pressure phase relations, and seismic structure of the Earth have yielded insights into the structure of the Earth's mantle beneath the oceans. These four topics are emphasized in this overview. The first topic will be covered in detail; the others will be largely referenced to recent literature and to other comprehensive papers in these volumes.

#### ACKNOWLEDGMENTS

This overview has benefited from my discussions over the years with many persons. In particular, Al Hofmann and Fred Frey have kept me aware of the contribution of isotopic and trace-element data to the study of Hawaiian geologic problems, whereas my own research has been principally concerned with major-oxide mass balances as they relate to constraints provided by geologic, geodetic, and geophysical information. I appreciate correspondence and preprints from D.L. Anderson. The manuscript has benefited from reviews by Christina Heliker, Dave Clague, and Rosalind (Roz) Helz. Roz' review resulted in a substantially expanded content, much of it her own ideas; therefore, she was included here as a coauthor.

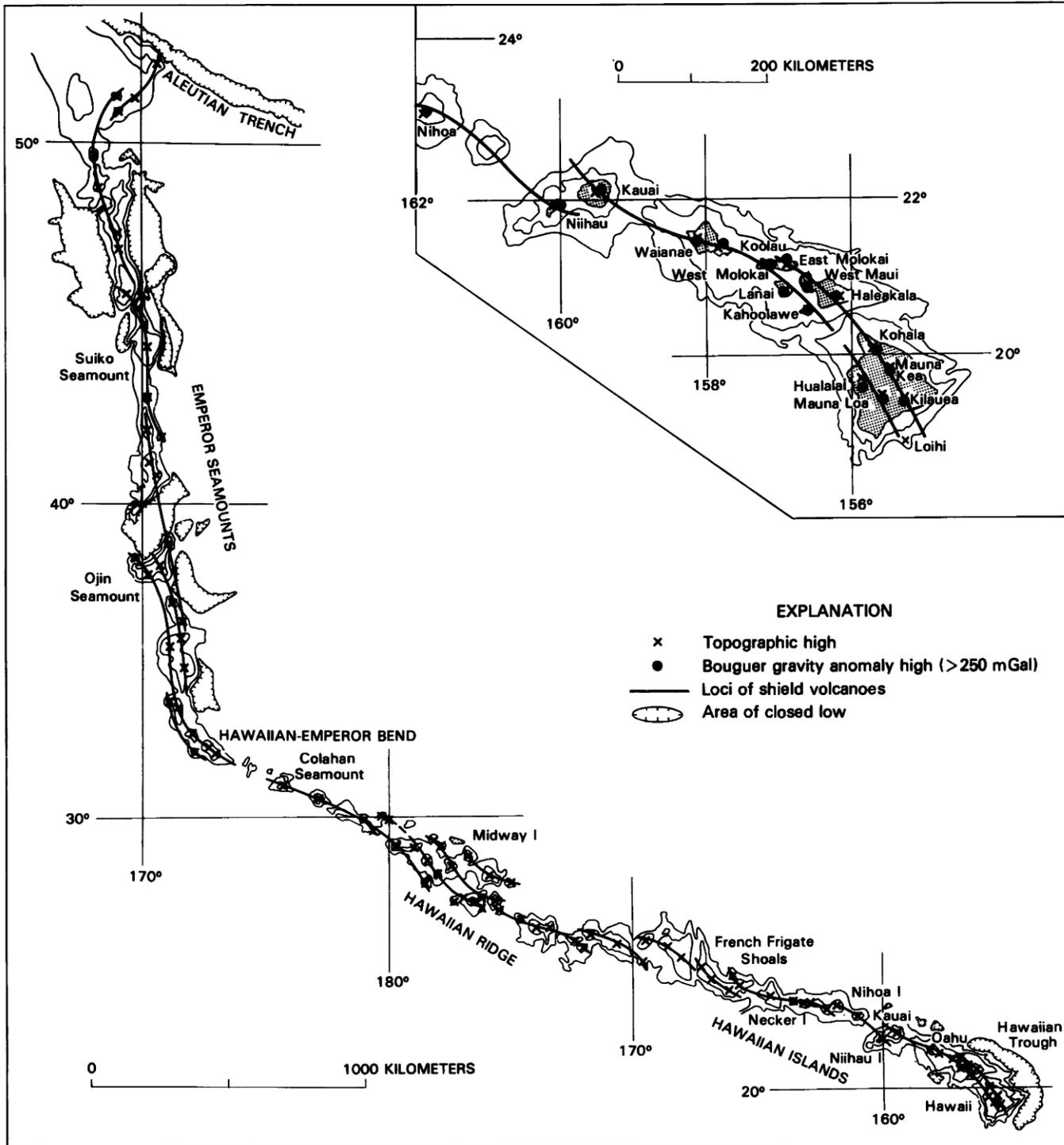


FIGURE 23.1.—Loci of shield volcanoes in the Hawaiian-Emperor Chain. Inset shows the detailed relation between topographic highs (crosses), Bouguer gravity anomaly highs (circles), and loci (heavy lines) for the principal Hawaiian Islands. From Jackson and others (1972).

### THOLEIITIC VOLCANISM: WHAT HAVE WE LEARNED?

Modern petrologic study of Hawaiian volcanoes began in the 1940's and 1950's with G.A. Macdonald's work on the development of Hawaiian volcanoes and his analyses of the different lava types (Macdonald and Katsuura, 1964), with H.A. Powers' (1955) recognition that olivine played a dominant role in tholeiitic differentiation, and with the work of Tilley and Scoon (1961), emphasizing chemical and mineralogic distinctions between lava from Kilauea and lava from Mauna Loa. These workers established that Hawaiian tholeiite ranges in composition from about 5.5 to 20 percent MgO, that lava with over 7 percent MgO had magnesian olivine as the dominant phenocryst, that lava with less than 7 percent MgO had augite and plagioclase in addition, and that Mauna Loa was distinguished from Kilauea by the presence of hypersthene, in combination with all three of the other silicate phases. Powers and Tilley had both demonstrated that once the chemical signature of olivine addition or subtraction has been removed, different tholeiitic volcanoes have subtly different compositions (the range of compositions related by a single set of olivine control lines are termed "magma batches") that characterized each volcano uniquely. Powers, in addition, had recognized that even more subtle variations occurred to produce separate magma batches within the products of a single tholeiitic shield.

Another level of inquiry began with modern studies at the Hawaiian Volcano Observatory, beginning about 1952, when Kilauea became active after 18 years of dormancy. From 1952 to the present (1986), every eruption has been sampled and analyzed, and eruptions that extended over periods of days, weeks, or even years, have been sampled at regular intervals to cover both the spatial and temporal distribution of eruptive products. This sampling is of critical importance because significant changes in lava composition during an eruption have occurred, and earlier (particularly the earliest) eruptive products are likely to be covered by later phases of the eruption and thus never encountered in conventional studies of older lava. This burial process is amply demonstrated, for example, by the 1983–1984 eruption of Kilauea (see Wolfe and others, chapter 17).

In another development, the occurrence of a series of eruptions in pit craters (1959, 1963, 1965) provided molten lakes of tholeiitic basalt for large, outdoor laboratory experiments in the cooling and crystallization of basalt. These studies were complementary to a study made of a prehistoric lava lake exposed in the walls of Makaopuhi Crater (Moore and Evans, 1967; Evans and Moore, 1968). In the next two subsections we address first what we have learned from the lava lakes, and secondly, we apply this information to interpret petrologic processes important to understanding the entire sequence of eruptive activity from 1952 to the present.

#### KILAUEA LAVA LAKES

Core drilling in the lava lakes, after they crusted over, provided a means of studying the processes of crystal-liquid movement during slow cooling. An overview of the importance of the lava-lake studies with a description of what was done on each lake, including an

annotated bibliography, was written by Wright and others (1976). Subsequently, papers on the March 1965 Makaopuhi lava lake (Wright and Okamura, 1977), the August 1963 Alae lava lake (Peck and Kinoshita, 1976; Peck, 1978; Wright and Peck, 1978), and thermal-modeling studies (Peck and others, 1977; Shaw and others, 1977) have contributed further details; Peck and others (1979) demonstrated the breadth of interest in the lava lakes. Makaopuhi and Alae have both been covered by subsequent eruptions, further attesting to the value of real-time volcanic studies. The November–December 1959 Kilauea Iki lava lake, documented by Murata (1966), Murata and Richter (1966), Richter and Moore (1966), Richter and Murata (1966), and Richter and others (1970), is still being studied. Drilling programs in 1976, 1979, and 1981 were performed as a joint project of the U.S. Geological Survey and Sandia National Laboratories. Geophysical results of the 1976 drilling are given by Hermance and Colp (1982), and a description of the 1981 drilling is given by Hardee and others (1981). Thermal modeling of the lake (Hardee, 1980) and a study of the seismic structure of the lake (Chouet and Aki, 1981) have also been accomplished. Further petrologic results are reported by Helz (chapter 25; 1980) and by Helz and Wright (1983). Description of drill core is provided by Helz and Wright (1983) and by Helz and others (1984). New interpretations of the mechanics of the 1959 eruption are given by Eaton and others (chapter 48) and by Helz (chapter 25).

The studies of Alae and Makaopuhi lava lakes have quantitatively documented several processes of importance to Hawaiian petrology. These processes include the following:

(1) Settling of olivine occurs under the influence of gravity at temperatures greater than 1,150 °C. This settling is by no means as straightforward a process as that predicated by theory, as it can be shown that the observed rates of settling are far less than those predicted by Stokes' law. This difference is partly due to the presence of gas bubbles moving upward as olivine is sinking, thus impeding the progress of both, and partly to the fact that the liquid behaves as a Bingham fluid, as was discovered by direct experimentation in Makaopuhi lava lake (Shaw and others, 1968). Further study of Kilauea Iki led to the suggestion that with a large population of olivine the crystals might settle with a boundary layer of melt, decreasing the rapidity with which olivine can be segregated (Helz, 1980, p. 693–696). Helz (chapter 25) has shown, in line with earlier studies of a frozen prehistoric lava lake (Moore and Evans, 1967; Evans and Moore, 1968), that olivine, after settling, rapidly re-equilibrates to more iron-rich compositions and that the final olivine composition may be very different from that present at the time of eruption. All of these data place constraints on the interpretation of olivine abundance in natural lava.

(2) Differential separation of augite and plagioclase occurs under the influence of convective flow at temperatures between 1,150 °C and 1,080 °C. This separation is a more subtle process than olivine segregation and is shown to occur at crystal sizes far smaller than those that could be gravitationally segregated in a reasonable time. Differential separation of augite and plagioclase is inferred to take place only in the absence of a separate volatile phase, because upward movement of vesicles will reverse the density gradients

needed to initiate convection in a body of molten basalt. The time at which convection in Makaopuhi lava lake was initiated has been inferred from thermal anomalies in temperature profiles taken in the melt, correlated with decreased vesicularity in core collected below a certain depth in the lake. Within months of the time at which convection was initiated, the bulk composition of the lava lake began to change in a manner reflecting loss of chemical components present in augite and plagioclase, in addition to those present in olivine (Wright and Okamura, 1977). A complementary effect of convective transfer is to enrich the margins and probably the basal parts of the lava lake in the components of augite and plagioclase, in addition to those of olivine, causing a chemical profile through a lava lake to depart from strict olivine control. The chemical effect is nicely shown in analyses from the lower part of the prehistoric Makaopuhi lava lake (Moore and Evans, 1967).

(3) Melt is physically segregated from a rigid crystal framework at temperatures below 1,080 °C. The lava lakes provide a quantitative demonstration of the process known as filter pressing, and they contribute toward an understanding of the origin of segregations of basaltic liquids with variably fractionated chemistry. Natural segregations are common in thick basaltic flows and sills throughout the world. The term "segregation vein" was applied to these bodies in the 19th century and has remained in use since. Basaltic segregations generally stand out from the host rock by their lighter color and coarser texture, and they commonly fill subhorizontal fractures. Segregation of this kind only occurs at temperatures below the critical temperature at which the lake behaves as a rigid body (see discussion in Wright and others, 1976). First demonstrated as an artifact of the drilling process (that is, melt flowing into open drill holes during thermal recovery toward predrilling temperatures), this process also results in natural segregations (segregation veins) where melt has flowed into zones of lower pressure. Most segregations have sharp contacts with the host rock, suggesting filling of an open fracture. Others have more subtle boundaries, suggesting that the wall rocks were ductile at the time of segregation. The presence of segregations is a function of the rate of cooling, and their orientation (that is, whether fillings are horizontal, vertical, or some other angle) gives important information on the stress distribution in the cooling lava. Whether segregation takes place is a function of temperature, which controls both the chemical composition and viscosity of the melt fraction, the rigidity of the crystal network, and the time during which a pressure gradient favorable to segregation is present. In the lava lakes, a combination of cooling curves and viscosity temperature relations limit the normal process of segregation to temperatures above about 1,050 °C, at which temperature melt compositions are still in the basaltic range. However, Kilauea Iki lava lake contains rare examples of small segregations of much more siliceous melt, with silica content as much as 70 percent. This mechanism may operate in basaltic intrusions to produce small bodies of rhyolite or dacite for later eruption as lava.

Several lines of evidence indicate that Hawaiian eruptions are supersaturated in volatile constituents at the time of eruption. Thus, the vesicle distribution in thick lava lakes is, in large part, a frozen record of incomplete volatile removal at high temperature. We must emphasize that lava erupted at, or under, saturation would behave

very differently in terms of processes defined for the Kilauea lava lakes.

Results of the study of Makaopuhi and Alae lava lakes define classic, closed-system fractional crystallization in which mass-balance calculations document various kinds of crystal movement in liquids that vary along a regular liquid line of descent (see Wright and Peck, 1978, fig. 4). The study of processes documented by study of major oxides have been extended to show that trace elements vary consistently with major oxide relations (Lindstrom and Haskin, 1984).

Kilauea Iki, the remaining lava lake, is distinguished from Alae and Makaopuhi by its more magnesian bulk composition (average MgO content is 15–16 weight percent), larger volume, and more complex filling history. As a result, the core obtained from Kilauea Iki shows many features unlike those seen in the other lava lakes. For example, core recovered below 12 m depth has a chemistry that does not fit the olivine-controlled chemistry defined by samples collected during the eruption (Wright, 1973). Although, by definition, this lava lake also represents a closed system, the mass balances relating the chemistry of crystallizing minerals, liquid segregation, and bulk rock at different levels in the lake depart significantly from the rather straightforward relations summarized in papers on the other lava lakes. Fractionation processes identified in Kilauea Iki are listed below. Some of these processes occur at higher temperatures than in the other lakes (Nos. 1, 2, and 5), whereas others have been observed only in Kilauea Iki (Nos. 3, 4, and 6).

(1) Gravitational settling of coarse (>2 mm) olivine, resulting in a zone in which large olivine crystals are absent, occurring between 20–40 m below the surface of the lake. The composition of the moving olivine averaged  $Fo_{86}$ , that is, the chemistry of the drill core defines a set of olivine control lines on variation diagrams of  $Al_2O_3$  versus MgO or  $SiO_2$  versus MgO that extrapolate to an olivine composition of  $Fo_{86}$ . This composition implies that temperatures were  $\geq 1,180$  °C in the part of the lake through which the olivine settled (Helz, 1980; Helz and Thornber, in press).

(2) Horizontal redistribution of augite microphenocrysts, by convection. Within the olivine-depleted zone, small (1–2 mm) clots of augite microphenocrysts are present in core from near the edge of the lake and absent in the middle. This differential concentration of augite raises the CaO content of the core from 10.5 weight percent in the middle to 11.6 weight percent at the edge. In contrast to Makaopuhi, this flow differentiation has not involved plagioclase, hence it occurred only at temperatures above 1,160 °C.

(3) Diapiric upwelling of lower density melt from within the olivine-rich mush at the base of the lens of melt. The moving liquid is that present at temperatures of 1,145–1,160 °C, just below the incoming of plagioclase. This liquid is inferred to rise to the uppermost part of the lens of melt where it mixes with the melt just below the base of the upper crust. This process causes the lava below 12 m to deviate from olivine controlled chemistry. The upper mixed zone is enriched in low melting constituents such as  $TiO_2$  and alkalis and is depleted in FeO and CaO relative to what would be expected for olivine-controlled chemistry (Helz, 1980). The source region undergoes complementary depletion in  $TiO_2$  and alkalis relative to olivine-controlled chemistry. Helz (1980), citing data for

the upper, enriched zone only, tentatively described the enrichment to filter pressing of liquid formed during partial remelting of foundered crust deep in the lake. Recovery and analysis of deeper core has led to our present recognition that, first, this process does not require foundered crust, and second, it has affected the chemistry of the lava at virtually all levels in the lake. This process occurs only in olivine-rich rock. The requisite density inversion is much smaller in melts in bulk compositions with MgO  $\leq 7.5$  percent. Hence, this process would not have been expected to occur in the other lava lakes.

(4) Diapiric rise of streams of vesicles with or without entrained melt, from within the lower crust. The vesicles first entrain melt, then coarse olivine from the lower part of the lake. As the plume rises into cooler material it begins to segregate, with the vesicles and melt detaching themselves from the trail of coarse olivine. These trails remain as vertical olivine-rich bodies, which can be seen in every drill core recovered from Kilauea Iki between 40 and 58 m (Helz, 1980). These olivine-rich bodies contain excess iron-rich olivine ( $F_{0.77-79}$ ) and differentiated liquid (temperature range of 1,140–1,120 °C), relative to the adjacent host rock, so they are active at lower temperatures than the diapirs in process 3. Analogous vuggy, vertical bodies also are present between 26 and 40 m, but they are much harder to spot as they lack coarse olivine (Helz, 1980). The melt- and vesicle-rich top of the vertical olivine-rich bodies looks like a segregation vein, which led Helz (1980) to suggest that segregations might be related to these bodies in some way. Similar bodies, described as "indistinct, pipe-like masses rich in olivine" occur in the lower part of the prehistoric Makaopuhi lava lake (Moore and Evans, 1967), though in that lake there was no evident connection with segregation veins.

(5) Formation of segregation veins, which are coarse-grained diabasic sills, generated by processes internal to the lava lake. Segregation veins in Kilauea Iki are more abundant than in the other lakes and form an apparently continuous set of sills, concentrated between 18 and 56 m, where they comprise 5–10 volume percent of the lake (Helz, 1980). Their bulk compositions correspond to liquids produced at 1,135–1,100 °C, using the calibration of Helz and Thornber (in press). In Kilauea Iki, segregation veins are more magnesian and presumably form at higher temperatures than those in Alae and Makaopuhi.

(6) Filling of late fractures or large vesicles by highly differentiated liquids, produced at 1,060–1,000 °C. The fractures are produced by brittle failure of the lake lava as it shrinks during crystallization and cooling. The bulk compositions of these tiny bodies are andesitic to rhyolitic ( $SiO_2$ , 56–70 weight percent, MgO, 0.5–3.0 weight percent); their existence demonstrates the mobility of interstitial liquid even when very little (<10 percent melt is present (Helz, 1984). The driving mechanism is inferred to be gas filter-pressing (Anderson and others, 1984).

In addition to these processes involving differential movement of crystals, vesicles, and liquid, Kilauea Iki illustrates very well the extent to which interstitial liquid compositions are controlled by local bulk composition. As discussed in Helz (1984), interstitial liquid becomes progressively depleted in FeO as olivine content increases. Other oxides ( $SiO_2$ ,  $Al_2O_3$ , alkalis) increase as FeO decreases,

whereas a few oxides (MgO, CaO,  $TiO_2$ ) are buffered by the phase assemblage. Thus, at a given MgO content of interstitial liquid, the liquids in olivine-rich rocks are richer in  $SiO_2$  and alkalis than liquids in olivine-poor rocks or segregation veins. Where a segregation vein occurs in an olivine-rich host, the difference in glass composition across the contact can be as great as 4 weight percent FeO within a single thin section.

The later stage mineral assemblages closely reflect these variations in interstitial melt composition. In olivine-rich rock, the low-calcium pyroxene is orthopyroxene (opx), the dominant Fe-Ti oxide is ferropseudobrookite (fpsb). With decreasing olivine content opx is replaced by pigeonite, and the oxide assemblage changes to fpsb + ilmenite, fpsb + ilmenite + magnetite, and finally ilmenite + magnetite, as observed in the low-MgO lakes Alae and Makaopuhi.

Thus, gravitative settling of olivine, followed by closed-system crystallization, has created a magma chamber in which different liquid lines of descent are being generated in rocks meters apart. Important implications of these observations, applied to larger differentiating chambers, are that one chamber may be capable of erupting two or more dissimilar lava series produced solely by processes operating within the chamber and not necessarily from different sources.

#### TIME-SPACE RELATIONS OF KILAUEA LAVA

Studies based on the chemistry of erupted lava from 1952 to 1985 have extended our knowledge of differentiation processes in Hawaiian tholeiite. Interpretation of Kilauea's chemistry is also dependent on seismic and geodetic studies (Eaton and Murata, 1960; Eaton, 1962), which clearly identify a complex holding reservoir beneath the Kilauea summit through which magma for eruptions anywhere on the volcano must pass (fig. 23.2; also see Wright and Fiske, 1971, fig. 9; Ryan and others, 1981). Helz (chapter 25) presents data that supports the earlier suggestion of Wright (1973) that magma erupted in 1959 is an exception and might have bypassed storage in the normal summit-reservoir complex. Two early summaries (Wright, 1971; Wright and Fiske, 1971) document the general changes of bulk chemistry with time, quantify the concept of olivine control, describe the differentiation processes operating within Kilauea's rift zones, and treat the problem of magma batches and the mixing of liquids of different composition prior to eruption. A model was developed in Wright and Fiske (1971) in which magma batches of subtly differing bulk chemistry arrive in the storage complex beneath Kilauea summit and are displaced to higher levels in the storage complex, where they become chemically zoned due to gravitational settling of olivine as newer batches of olivine-rich magma arrive from the mantle. During eruption or intrusion within the rift zones, some portion of magma moving into the rift is separated from the main source of heat, resulting in cooling and differentiation. Rift eruptions are inferred to be fed from the lower parts of the summit reservoir complex and, more often than not, mix with fractionated magma present from previous episodes of rift intrusion to form hybrid magma. Because of

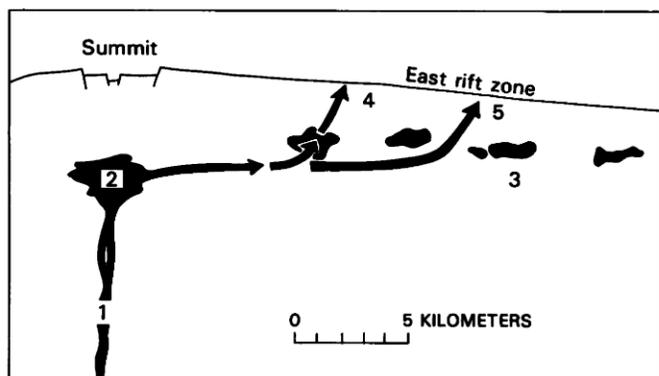


FIGURE 23.2.—Simplified model of magma storage and eruption at Kilauea (modified from Wright and Fiske, 1971, fig. 9): (1) Conduit through the oceanic crust defined seismically; (2) shallow storage reservoir, defined from both geodetic measurements and as an aseismic zone; (3) isolated pockets of magma produced by intrusions into the rift zones. Eruptions at the summit are fed directly from the top of the central reservoir. Most eruptions on the rift are also fed from lower in the central reservoir and may either become mixed with stored rift magma (4) or have direct access to the surface (5). Infrequently, stored rift magma may be erupted independently.

the compositional layering in the summit reservoir resulting from the sequence of magma batches supplied from the mantle, rift eruptions tend to be richer in olivine than summit eruptions and have a summit component in their composition that predates eruption of that component at the summit. These inferences were presented for Kilauea eruptions through 1974 in Wright and Fiske (1971), Wright and others (1975), and Wright and Tilling (1980).

In 1971 and 1974 intrusions beneath the south part of Kilauea caldera were evident (Duffield and others, 1982; HVO, unpublished data). These intrusions resulted in development of mildly differentiated lava as a component of subsequent hybrid eruptions at Kilauea summit in 1974 and 1982 (Wright and Tilling, 1980; HVO, unpublished data).

Direct eruption of fractionated lava on the east rift zone occurred in 1955, 1962, and 1968 (see Wright and Fiske, 1971; Wright and others, 1975) and again in 1977 (Moore and others, 1980) and 1983 (Wolfe and others, chapter 17; Garcia and others, in press). The parent composition, time of rift storage, and rate of crystallization in storage have been quantitatively determined for recent mildly fractionated lava (see Wright and Tilling, 1980). The processes of differentiation within the rift zone appear to be very similar to both the high-temperature and low-temperature differentiation observed in Makaopuhi and Alae lava lakes, suggesting that magma in storage is under sufficient pressure to maintain volatile components in solution, thus enabling convection to take place, and that lower temperature segregation can sometimes occur on a large scale, creating separate reservoirs of fractionated magma. The 1955 eruption requires the latter, as the early erupted lava shows an intratelluric phenocryst assemblage (hypersthene, augite, plagioclase, Fe-Ti oxides) very different from the normal assemblage of olivine and minor augite and plagioclase characterizing lava whose bulk composition is unfractured.

In addition to study of petrologic processes demonstrated in single eruptions, it should be eventually possible to quantitatively evaluate the times of arrival of magma batches from the mantle, specify where these batches will be stored and for how long, and relate these to when and where they will be erupted to the surface. The seismic data on earthquake swarms related to magmatic intrusions (Klein and others, chapter 43), combined with detailed petrochemical study (for example, Wright and Tilling, 1980), should provide the basic data to do this within the broad framework of geodetic and geophysical observations related to magma storage (Dzurisin and others, 1984).

The processes defined at Kilauea are by no means restricted to Hawaiian tholeiite. The same processes of storage, fractionation, and mixing of magma have been amply documented for midocean ridge basalts (see, for example, Basaltic Volcanism Study Project, 1981, p. 132–160). Thus, both voluminous oceanic basalt types, whose chemistry remains fairly constant with time, behave similarly in spite of the differences in bulk chemistry. However, studies of recent Hawaiian eruptions illustrate a problem that must be considered in looking at older basaltic lava sequences in Hawaii and elsewhere; that is, samples from a single stratigraphic section may represent only a fraction of the lava from any single eruption, and significant compositional changes that occurred during the eruption may be missed. Interpreting contacts between flows to define related eruptive sequences is virtually impossible in older flows, especially in flows of small volume. In the prehistoric record, contacts preserved in a sequence of flows from Mauna Ulu (1969–1974) may look no different than a contact between lava erupted in 1961 and any one episode of Mauna Ulu that happened to cover it. This possibility underscores the fact that petrologic studies of older lava fields may lack much of the critical information that is made available when an eruption or sequence of eruptions is actually observed.

#### COLLECTION AND ANALYSIS OF HAWAIIAN GASES

One of the most important opportunities afforded by active volcanoes is the sampling of volatile constituents either from active fumaroles or during eruptions. Collection of usable gas samples at an active vent is far from an easy task, as it entails being able to approach an erupting fissure or lava pond, collect a sample with minimal atmospheric contamination, and analyze the sample within hours of collection in order to prevent reaction of the gas species with one another. Some of the best samples ever obtained were collected in the early 20th century from the continuously active lava lake in Kilauea caldera (Shepherd, 1921; Gerlach, 1980). Later in the century, collections were made through drill holes in Makaopuhi lava lake (Finlayson and others, 1968) and the 1977 eruption of Kilauea (Graeber and others, 1979). In 1980, permanent gas analysis facilities were established at the Hawaiian Volcano Observatory. Greenland (chapters 28 and 30) summarizes information on extensive collections of gases from Kilauea and the first modern samples of eruptive gases from Mauna Loa. Franczyk and others (chapter 31) give complementary data on the amount of carbon and sulfur that remains in the lava after eruption.

The importance of volcanic gas analyses lies both in the estimates of primary volatile compositions of magma and in the budget of volatile species put into the Earth's atmosphere as a result of volcanic eruption. The latter subject is addressed by Casadevall and others (chapter 29) and by Gerlach and Graeber (1985). Volcanic pollutants, mainly CO<sub>2</sub> and SO<sub>2</sub>, are found to be significantly less than the contribution from modern industry. The composition of gases arriving from the mantle, after storage beneath Kilauea summit, and residual gas left in erupted lava is estimated for Kilauea (table 23.1) using data of Greenland and others (1985). These estimates are close to those made by Gerlach and Graeber (1985). Estimates of volatile budgets for the 1983–1985 Kilauea eruption also provide an estimate of volatile emission rates consistent with magma supply rates obtained by seismic and geodetic methods (Gerlach and Graeber, 1985; Greenland and others, 1985). Finally, study of gases from the ongoing Kilauea east rift eruption has led to estimates of the rates of magma ascent in the conduit, the diameter of the conduit, and the vertical gradients of pressure and density within the magma column (Greenland and others, in press).

#### PETROLOGY IN CONTEXT: A MODEL FOR STORAGE AND TRANSPORT OF KILAUEA MAGMA

Petrologic and geochemical studies at Kilauea are not in themselves sufficient to translate chemical variations into physical processes. The framework for interpretation of time- and space-related petrologic processes at Kilauea is provided by seismic and geodetic studies. These studies provide direct evidence both for regions of magma storage and for the distribution of and relief of stress associated with magma movement at crustal and upper mantle depths (see Decker, chapter 42). A primary storage region beneath Kilauea summit is defined both seismically (Koyanagi and others, chapter 45, part I; Thurber, chapter 38; Koyanagi and others, 1976) and from ground deformation measurements (for example, Fiske and Kinoshita, 1969; Dvorak and others, 1983). Secondary, and apparently transient, areas of active storage in the rift zones are also defined by a combination of seismic and geodetic measurements (see Klein and others, chapter 43, Jackson and others, 1975; Swanson and others, 1976b). Ryan and others (1981) have incorporated both kinds of data into a generalized three-dimensional model for Kilauea.

A simplified, two-dimensional representation of magma transport and storage is shown in figure 23.2. The depth to both primary and secondary storage is from about 2 km to 6 km beneath the ground surface. The summit storage reservoir is approximately the volume of Kilauea caldera minus the lava flows of historical age that have partially filled it; massive draining of the reservoir has probably occurred during caldera formation in the past.

The rate of magma supply to the Hawaiian system, as estimated from calculated volumes of dated volcanic edifices, is greater for the Island of Hawaii than at any time past (Clague and Dalrymple, chapter 1, part I; also see Moore, chapter 2, for an alternative interpretation). The magma supply to Kilauea, estimated from geodetic and gravity data, is intruded as dikes and sills and

TABLE 23.1.—H<sub>2</sub>O-CO<sub>2</sub>-S budget in Kilauea magma

[Values reported are in weight percent]

	H <sub>2</sub> O	CO <sub>2</sub>	S
Magma arriving from mantle	0.32	0.32	0.09
Magma after storage and before eruption	.28	.03	.08
Residual volatiles in erupted lava	.05	<.01	.02

extruded as flows in nearly equal amounts; this relation appears to be constant over periods of years (Swanson, 1972; Dzurisin and others, 1984). Recent evidence suggests that the magma supply to Kilauea has increased over the past decade (see Wolfe and others, chapter 17; Greenland and others, 1985). The passage of magma into the rift zones causes a buildup of strain in the south flank that is marked by changes in length of geodetic lines and by high seismicity. The strain is relieved when the unbuttressed south flank of Kilauea moves oceanward (Swanson and others, 1976a). Seismicity, associated both with the rift zones and the south flank, is also high during intrusion or during emplacement of a dike preceding eruption at a new location. Commonly earthquake epicenters migrate ahead of the dike tip to define the magma transport path (see Wolfe and others, chapter 17; Koyanagi and others, chapter 45, part I; Klein and others, chapter 43). Long continued eruptions such as Mauna Ulu (1969–1974) or the current Kilauea eruption at Puu Oo (Wolfe and others, chapter 17) create an open transport system in which seismicity along transport paths is greatly reduced (Koyanagi and others, chapter 45, part I).

Magma supply from the mantle during 1952–1975 was describable in terms of batches of distinct composition (Wright and others, 1975; Wright and Tilling, 1980). Following a large south flank earthquake ( $M=7.2$ ) in 1975 (Lipman and others, 1985), magma compositions during 1979–1984 were no longer easily divided into discrete batches. Possibly the earthquake effectively broke down internal boundaries in the storage system, so that stored magma and new magma mixed on a large scale. An earthquake of similar magnitude occurred in 1868 and had an apparent effect on both the subsequent rate of eruption and chemical composition of lava from Mauna Loa (Lockwood and Lipman, chapter 18; Tilling and others, chapter 24). This effect further emphasizes the need to know volcanotectonic constraints in order to properly interpret petrochemical data.

The high rates of magma supply from depth in the past decade are also reflected in patterns of deeper seismicity. A zone between 15 and 30 km depth (that is, in the very uppermost mantle) is less seismic than the regions above and below, perhaps defining, as with the lowered seismicity around shallow rift transport systems, a greater openness of the magma transport path (Koyanagi and others, chapter 45, part I).

The distribution in time and space of deep tremor and long-period earthquakes is of great significance, providing evidence for magma movement at depths of 40–60 km (Koyanagi and others,

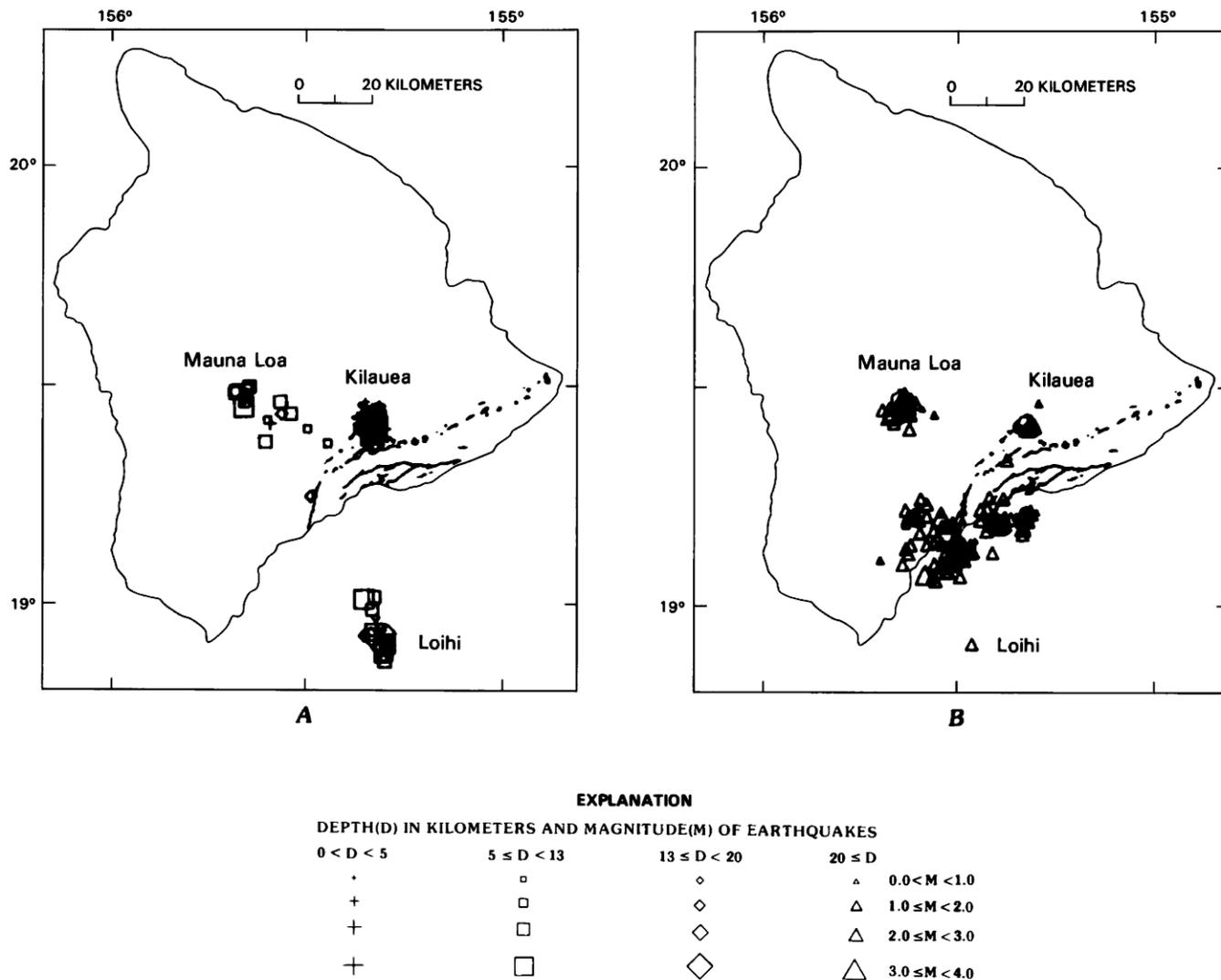


FIGURE 23.3.—Long-period seismicity of the Island of Hawaii, 1972–85. **A**, Epicenters of long-period earthquakes with hypocenters <15 km deep. Note clustering at the three active volcanic centers. **B**, Long-period earthquakes and locatable bursts of harmonic tremor with hypocenters >30 km deep (maximum is about 55 km). Note the dominant clustering in a broad zone between the three active volcanic centers.

chapter 45, part I; Klein, 1982). The zone of deep, long-period seismicity is centrally located with respect to all three active volcanoes—Loihi, Kilauea, and Mauna Loa—contrasting with the concentration of shallow long-period earthquakes in each volcanic edifice above and below the storage reservoir; these relations are shown in figure 23.3. The connections between deep and shallow transport systems are not clear. If, indeed, the zone shown in figure 23.3B defines the deeper end of magma transport systems for all three volcanoes, then it severely constrains the explanations for the distinctive chemistry and lava associations in each volcano. Either the zone of magma collection is compartmented at a scale not seen by the seismic data, or the chemical differences are produced in transit toward the surface, at much higher levels than the zone of melting.

Isotopic data, as currently understood, probably rule out the latter conclusion, leaving one with a challenge to relate the observed seismicity to magma transport in a way that preserves chemical differences that originate in the melting zones (see Chen and Frey, 1985, however, for discussion of the possible influence of the transport path to the surface on chemical and isotopic variation).

Deeper yet, the zone of melting beneath Hawaii has been postulated to be within the uppermost asthenosphere, at depths greater than 60 km (see Wright, 1984). The unique chemistries of magma at the three volcanoes suggest that discrete regions of melting within the asthenosphere each have their own isotopic and trace-element signature. This problem will be discussed further in the final section.

### LOIHI SEAMOUNT: A LOOK AT THE BEGINNING OF A HAWAIIAN VOLCANO

Loihi Seamount was discovered in 1955 from looking at a compilation of bathymetric data around the Hawaiian Islands (Emery, 1955). Later, with an expanded Hawaiian seismic net and a new computer system for locating earthquake foci, F.W. Klein and R. Y. Koyanagi noted swarms of shallow crustal earthquakes off the southeast coast of the Island of Hawaii (Klein and Koyanagi, 1979; Klein, 1982). Together, these observations suggested the existence of an active Hawaiian volcano in the making. Plans to dredge the seamount were carried out, samples were taken, more precise bathymetry was obtained, and preliminary results were published (Malahoff and others, 1982; Moore and others, 1982). A summary of more recent bathymetry and geophysical study is given in Malahoff (chapter 6). The dredge hauls contained both tholeiitic and alkalic basalt. Some of the latter contained xenoliths. Dating of samples showed an age range of from 0.5 to 1.6 ka, with alkalic basalt older, for the most part, than tholeiite. Thus, the newest volcano in the Hawaiian Chain showed apparent reversal in the accepted age relations of alkalic and tholeiitic basalt.

Research on Loihi was subsequently treated in a manner similar to the lunar program; we now know more about Loihi (isotopes, trace elements, major oxides) than any other single Hawaiian volcano (see Craig, 1983). Study of Loihi has generated many new questions about the growth of Hawaiian shields and the nature of the melting process(es). Workers on Loihi have concluded that the earliest stage of Hawaiian volcanism is alkalic. The Loihi data also raise the possibility that alkalic volcanism may occur at any stage in shieldbuilding, perhaps when the rate of melting in the mantle slows down for some reason. The bathymetry of the undersea portions of most Hawaiian volcanoes defines a shield shape, and this requires that the dominant shield-building lava be fluid tholeiite and that the alkalic component be at most a minor intercalation. All conclusions need to be tempered by the fact that above water we have sampled less than 10 percent of any Hawaiian shield, and the sampling at Loihi comprises only the surface lava on its shield.

Detailed petrologic and geochemical studies of Loihi (Frey and Clague, 1983; Hawkins and Melchior, 1983), combined with isotopic studies of Sr (Lanphere, 1983; Staudigel and others, 1984) and Pb and Nd (Staudigel and others, 1984), bring about the unanimous conclusions that significant heterogeneity exists within the Hawaiian hotspot and that it is difficult to relate Loihi samples with subaerial lava sequences. The tholeiite samples have a demonstrably Hawaiian chemistry that differs in small ways from both Kilauea and Mauna Loa. The alkalic samples differ from the subaerial alkalic caps on other Hawaiian volcanoes and from the nephelinitic series. Furthermore, these samples lack the garnet-bearing xenoliths of the latter series, but contain lherzolite xenoliths not found in the former series. Isotopic study of rare gases (Kaneoka and others, 1983; Kurz and others, 1983; Rison and Craig, 1983) unequivocally define the source material as primitive and undegassed mantle material, unmodified by crustal processes, relative to data from other volcanoes. Thus, the discovery and subsequent study of Loihi has provided additional constraints and new questions to be asked in relation to our understanding of Hawaiian volcanic cycles.

### PUTTING IT ALL TOGETHER: INTEGRATED MODELS OF THE PETROGENESIS OF VOLCANIC SEQUENCES IN THE HAWAIIAN ISLANDS

Earlier studies of Hawaiian volcanism were based on geologic mapping and sampling stratigraphic sections for petrographic study and major-oxide chemistry. Work on trace elements and isotopes was of a reconnaissance nature confined to widely scattered samples, only some of which were tied to major-oxide study. Compilation of these data resulted in generalities about the geochemical signature of Hawaiian volcanism and recognition of the systematic differences between midplate and midocean ridge volcanism (see, for example, summaries by O'Nions and others, 1977; Lanphere and Dalrymple, 1980; Basaltic Volcanism Study Project, 1981), but contributed little to understanding the details of the evolution of individual Hawaiian shields. Recently, more concentrated studies on specific volcanoes and stratigraphically defined sequences within those volcanoes have been undertaken to establish the details of isotopic, trace-element, and major-oxide behavior. These studies have focused on Molokai (Beeson, 1976; Clague and others, 1983), Kohala (Feigenson and others, 1983; Lanphere and Frey, in press), Kilauea (Casadevall and Dzurisin, chapter 13; Hofmann and others, 1985), Haleakala (Chen and Frey, 1983, 1985), Koolau (Stille and others, 1983; Roden and others, 1984), Kauai (Feigenson, 1984), and Loihi (see above). The Honolulu Volcanics have also been studied comprehensively (Clague and Frey, 1982). The principal conclusions reached from stratigraphic studies are the following:

(1) The transition from tholeiitic basalt to alkalic basalt at the end stages of Hawaiian volcanism is commonly, but not always, gradual, with interfingering of the two rock types with rocks of transitional chemistry.

(2) Sr isotopic signatures are inversely correlated to Rb/Sr ratios and may be systematically different for the tholeiitic shield, lower alkalic lava, and uppermost alkalic lava. The progression is subtle and is best illustrated by data from Haleakala using  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (Chen and Frey, 1983, 1985) for tholeiite (0.7037–0.704) through lower alkalic (0.7032–0.7035) and upper alkalic lava (0.7030–0.7033). In addition,  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios show a smaller variation and are inversely correlated to  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. These data are interpreted to show participation of different source regions in the formation of the three series. In other volcanoes, including Waiaanae, West Maui, and Mauna Kea, no systematic differences exist between radiogenic-isotope signatures in the tholeiitic and alkalic stages (Hegner and others, 1986; Stille and others, in press).

(3) Pb isotopes differ for each volcano, vary independently of Sr and Nd, and appear to be related to the age and location of individual volcanoes in the Hawaiian Chain (that is, to the Loa and Kea locus lines (fig. 23.1; see also Tatsumoto, 1978; Stille and others, in press). The absolute variation of all isotopic ratios and the uncorrelated variations of Pb with Nd and Sr have led workers in Hawaii to postulate mixing of at least three kinds of variably enriched or depleted sources. Beyond defining the need for three sources, no consensus has been made as to their position in the mantle or the details of their origin (see Tatsumoto and others,

chapter 26; Tatsumoto, 1978; Staudigel and others, 1984; Kaneoka, in press; Stille and others, in press).

Other geochemical studies, using trace and major elements, address further the relations between tholeiitic and alkalic volcanism. On the basis of field mapping, petrologic study of volcanic sequences, and experimental study of basaltic phase equilibria, two hypotheses have been proposed (see Macdonald, 1968, p. 512–516, for a good summary of these hypotheses). The first hypothesis, based principally on field studies and later on high-pressure phase equilibria, is that alkalic series on Hawaiian volcanoes are derived directly by fractionation of tholeiitic magma in storage. For this process to work, pressures must be great enough to stabilize hypersthene as a liquidus phase, the crystallization of which reduces the  $\text{SiO}_2$  of the derivative magma (see Green and Ringwood, 1964). This hypothesis is attractive from consideration of the very small volumes of the alkalic caps and was defended by Wright and others (1979) as a logical consequence of an active tholeiitic shield-building system breaking the connection with the hotspot as the plate drifts to the northwest. The second hypothesis, first presented by Kuno and others (1957), Yoder and Tilley (1962) and later, in modified form, by O'Hara (1965), all working with experimental data, postulates that alkalic magma is independently derived from a different source region at a greater depth than that which produced the tholeiite.

Evidence based on geochemistry shows that the first hypothesis is clearly untenable as a simple single-stage fractionation process, even for those volcanoes for which isotopic ratios are similar in the two rock types. Mass-balance calculations made using hypersthene as a dominant crystallizing phase satisfy major oxides, but leave minor and incompatible trace elements out of balance; that is, the alkalic basalt always has greater amounts of incompatible elements (K, P, light rare-earth elements, and so on) than can be explained by balancing  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , FeO, MgO, and CaO. Chondrite-normalized rare-earth-element patterns are always steeper for alkalic basalt than for tholeiite, a relation not explainable by removal of hypersthene in which solid-liquid partition coefficients for rare-earth elements are too low to significantly steepen the patterns for derivative liquids. The mismatch between trace elements and major oxides might be rectified in a model involving a continuously replenished magma system (see O'Hara, 1977). However, replenishment does not have much appeal in explaining the waning stage of Hawaiian volcanism. Hypothesis 1 is also difficult to apply to an earlier stage of alkalic volcanism, such as Loihi, where alkalic magma is preceding, rather than following, tholeiitic magma.

Modern evidence favors the first part of hypothesis 2, that the alkalic basalt is generated independently of the tholeiite in an isotopically different source mantle. The depths at which either type of magma is generated or last equilibrated is an unresolved issue. The identification of mantle metasomatism, isotopic heterogeneity, and possible mixing of source mantle materials with each other and with basaltic melt provide little certainty as to the absolute depths of generation of any basaltic melt, with the exception that the depths are in the mantle and below the deepest earthquake foci (60 km for Hawaii). At Loihi further complications arise. The data require simultaneous eruption of magma that has equilibrated at different

depths and that does not show the same isotopic relations as shown for the tholeiitic-alkalic transition at the end of Hawaiian volcanism.

The origin of the nephelinitic series, those containing modal nepheline and (or) melilite, is yet another story. Clague and Frey (1982) have exhaustively analyzed data for the Honolulu Volcanics on Oahu. They conclude that this series was produced at degrees of melting ranging from 5–11 percent and requires some premelting metasomatism of a garnet peridotite source. They specify melting at a pressure of 2.5–3.0 GPa, corresponding to a maximum depth of about 100 km. Other workers, for example Jackson and Wright (1970) and Wright (1984), favor an origin in the low velocity zone, deeper than 100 km. Because as much as 2 m.y. separates the truly nephelinitic series from underlying lava at the same locality, the nephelinite series should be only indirectly related to the thermal plume assumed to exist for the building of the large-volume Hawaiian shields. Jackson and Wright (1970, p. 427) hypothesized that post-erosional lava erupts due to release of pressure following the re-establishment of isostatic equilibrium, which was upset during the vast extrusions of shield-building lava. A more recent evaluation (Clague and Dalrymple, chapter 1, part I) finds that the time separating the shield-building lava and the uppermost alkalic lava is decreasing downchain and that the occurrence of post-erosional volcanism maintains a constant distance from contemporaneous shield-building activity. This evaluation is consistent with the Jackson-Wright model.

## MELTING MODELS AND THE NATURE OF THE HAWAIIAN MANTLE

Numerous recent models for Hawaiian volcanism have been based on very different premises and data sets. Not surprisingly, the various authors come to different conclusions regarding some of the fundamental facts needed to specify the history of Hawaiian magma from its source in the mantle to its eruption at the Earth's surface. These facts are, in part, the following, each of which has been or needs to be ascertained for each major rock type or stage of volcanism, that is, shield-building tholeiite, preshield and caldera-filling alkalic basalt, and uppermost alkalic to nephelinitic rocks.

1. Mantle sources: depth, mineralogy, and bulk composition.
2. Depth of partial melting.
3. Melt fraction produced at time of melting.
4. Degree to which primary magma is changed on the way to storage in the shallow crust or to eruption, for example, loss of olivine, interaction with wall rocks, and mixing during ascent.

An excellent summary of current models to explain the Hawaiian magma system is presented by Frey and Roden (in press). The geochemical models are grouped into those based primarily on isotopic data (Kaneoka, chapter 27; Kaneoka, in press; Tatsumoto and others, chapter 26; Staudigel and others, 1984; Stille and others, in press), those based on trace-element data (Leeman and others, 1980; Clague and Frey, 1982; Hofmann and White, 1982; Budahn and Schmitt, 1985), or those based on a combination of isotopic and chemical data (Chen and Frey, 1983, 1985; Feigenson, and others, 1983; Feigenson, 1984; Roden and others, 1984;

Hofmann and others, 1984; Clague, in press; Feigensen, in press; Lanphere and Frey, in press). The geochemical models are in general formulated to fit established geochemical assumptions (such as nonfractionation of isotopes and chondritic source compositions) and pay little attention to either geophysical considerations or the constraints afforded by study of active volcanism. Some additional models (Presnall and Helsley, 1982; Sen, 1983) are based on the interpretations of geophysical data and on experimentally determined phase equilibria for basalt and for mantle rocks, but fail to apply their interpretations to actual geochemical balances. Anderson (1981) has proposed models based on seismologic data using the velocity structure of the mantle and has attempted to reconcile these models with the existing geochemical data, again without quantitative verification. Wright (1984) has considered geochemical balances consistent with the physical processes involved in constructing an Hawaiian volcano. However, the various authors find little agreement on items 1–4 above.

On item 1, disagreement arises as to the existence of a deep mantle plume, whether such a plume would supply the material to be melted (as opposed to the heat for melting at upper mantle depths), and as to the nature of the residual assemblage after melting. The  $^3\text{He}/^4\text{He}$  ratios for some volcanoes support, in a striking way, the primitive nature of Hawaiian magma sources (see Kaneoka, chapter 27). Additional constraints on mantle sources, as determined by study of rare gas data, are given by Clague (in press). As noted earlier, there is agreement that several isotopically distinct sources participate at some point prior to melting and (or) storage at crustal levels. On the composition of the residual assemblage present after melting, two extreme views are presented: (1) Budahn and Schmitt (1985) use convergence of chondrite-normalized rare-earth-element patterns at the heavy end to infer the necessity of garnet in the residual assemblage for melting all Hawaiian basalt, and (2) Wright (1984) argues for a metasomatic process by which the garnet-like rare-earth-element signature is imparted to a depleted mantle source formed by melting of midocean ridge basalt before melting to produce Hawaiian tholeiite.

Most workers agree on item 2 that the actual partial melting occurs at uppermost mantle depths (that is,  $100 \pm 50$  km) but disagree as to whether lithosphere or asthenosphere is directly melted. Presnall and Helsley (1982) and Sen (1983) favor lithospheric melting, which has been strongly criticized on both geochemical and physical grounds (see Feigenson, in press). Most authors favor primary melting of the asthenosphere. Wright (1984) differs from both in postulating that melting takes place in asthenosphere that begins as oceanic lithosphere, but through a combination of metasomatic enrichment and lithospheric thinning was converted to asthenosphere before melting. Chen and Frey (1983, 1985) propose that melts are generated in the asthenosphere and subsequently modified during passage through the lithosphere.

Arguments about item 3 follow from the consideration of residual assemblages. The geochemical models, whether using incompatible element enrichment, or garnet as a residual phase, infer small (less than 10 percent) degrees of melting, even for tholeiite. This model results in a conundrum regarding the supply of material to be melted. As aptly stated by Chen and Frey (1983, p. 789)

“the entire lower lithosphere and much of the asthenosphere beneath a Hawaiian volcano must be involved in its creation.” Hofmann and others (1984) in a study of short-term chemical variation at Kilauea, remain noncommittal on absolute degree of melting, although their requirement that garnet be a residual phase restricts the degree of melting to less than 20 percent, in consideration of high-pressure phase relations in ultramafic systems. O’Hara (1985) points out some important constraints on assumptions of the degree of partial melting, based on evaluation of the real shape of the melting anomaly.

Conclusions regarding item 4 are largely a consequence of inferences made for items 1–3. As stated above, isotopic data appear to require a more complicated history than one might infer from other data. The existence of magma batches at Kilauea (see Wright and others, 1975) requires heterogeneity, either inherited from the melt source or produced between initial melting and shallow storage. Even this concept (that is, magma batches at Kilauea), carefully outlined in a series of papers (Wright and Fiske, 1971; Wright and others, 1975; Wright and Tilling, 1980), has been questioned by Hofmann and others (1984), who claim that the data define a continuum in all elements. We disagree and leave this subject as a point to emphasize how difficult it is to reach a consensus of interpretation on any observations of Hawaiian volcanism.

Finally, Anderson (1984, 1985) has questioned all of the conventional ideas regarding items 1–4. He favors a source for magma in the transition region at 200–250 km depth where large scale melting is followed by processes such as eclogite fractionation during ascent and mixing with melts from enriched mantle at shallow depth, to produce the rocks forming both the oceanic crust and the oceanic islands such as Hawaii. Time will tell whether these provocative ideas can be quantified and tested against all of the geochemical and geophysical constraints provided by study of active volcanism.

One additional way of determining the composition of the mantle and the melting process is through study of xenoliths brought up with basalt. The processes by which xenoliths arrive at the surface of the earth is somewhat enigmatic. Both tholeiitic magma and alkalic magma show abundant evidence of shallow storage, although the general absence of mantle inclusions from tholeiite and their frequent association with alkalic magma remains unexplained. Clague (in press) suggests that xenoliths are filtered out of tholeiitic magma during storage in large magma chambers. Wright (1984) makes a further suggestion that the rates of tholeiitic-magma transport are too slow and the coalescing transport paths too thin to permit xenoliths to arrive at the surface. Nephelinitic magma is inferred to erupt directly from the mantle and carry the only lherzolite and garnet-bearing xenoliths. Frey and Roden (in press) provide an excellent summary of the relations of xenoliths to both basalt and mantle sources. They point out that virtually all xenoliths have undergone modification prior to their inclusion in the ascending magma in the form of interaction with fluids that may change trace-element content, isotopic ratios, or deposit hydrous minerals. Therefore, because of these factors, combined with their small size, no xenolith can be interpreted as representing the bulk mantle, or any part of the mantle large enough to be considered as a source

composition in melting models. Nonetheless, their presence is useful in assessing the depth of origin of some Hawaiian basalt.

Perhaps no single model works for all volcanoes in the chain. As Frey and Roden (in press) point out, a problem in developing a general model is that it must explain both the unique geochemical features that characterize individual Hawaiian volcanoes and simultaneously explain the geochemical variations among all Hawaiian volcanoes. As a final point, we want to reemphasize the necessity for comprehensive study of everything relevant to construction of an individual Hawaiian volcano as well as the entire volcanic chain (see Wright and others, 1979; Wright, 1984). Recent advances in our understanding of seismology (Anderson and others, 1984), phase relations of ultramafic rocks (Takahashi and Scarfe, 1985; Walker and Herzberg, 1985), and the physical processes of melt separation (MacKenzie, 1984; Richter and MacKenzie, 1984) may eventually resolve both the depth and degree of partial melting in a way that can accommodate the constraints provided by active volcanic processes.

### SUGGESTIONS FOR FURTHER STUDY

The acquisition of more chemical data on Hawaiian lava has increased our qualitative and quantitative understanding of Hawaiian petrology and has also raised new questions for further study. Obviously, the location of Hawaii, in the interior of an oceanic plate far removed from influences of spreading centers or continental margins, continues to provide a setting in which possible determinations can be made as to the nature of the oceanic crust and mantle and the dynamics of plume or hotspot volcanism. Presently the heterogeneities in the hotspot magma sources are being emphasized. Yet over the long term it is important to keep in mind that the Hawaiian chain has shown an identifiable eruptive style and geochemical signature for over 70 million years. Thus, a gross uniformity must exist in the source and some unifying principles in the production of Hawaiian magma, the mechanics of its segregation from the mantle, and its transport to areas of storage within the crust. Further study of the following topics ought to bring us to a better understanding of the processes important in the formation of Hawaiian volcanoes: (1) Continued detailed geochemical study of stratigraphically constrained samples; (2) geophysical study of the mantle; (3) more detailed petrographic study (both field and thin section) of lava samples, including detailed electron probe analysis of phase chemistry; and (4) more study of the submarine portions of active or young rift zones. For example, cursory petrographic study of submarine rift samples identified mineral forms and textures such as anhedral olivine and sieved plagioclase that suggest that processes involved in submarine lava are different from those in subaerial equivalents on the same rift zones.

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