VOLCANISM IN HAWAII

VOLUME 1

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1350

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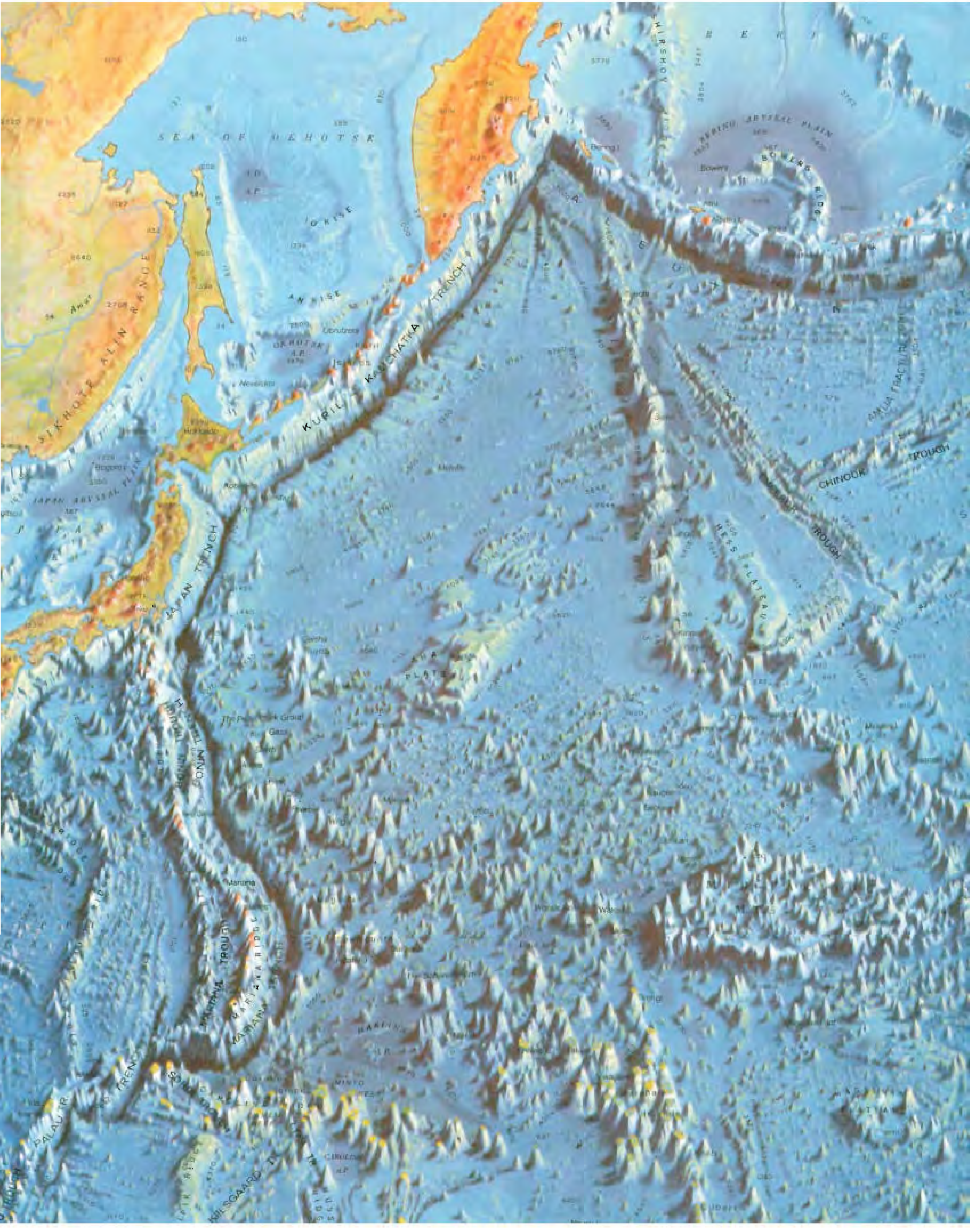
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Kodiak
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Seaward Channel
Surveyor Channel
Quinn
Pratt
Welker
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Pathfinder
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Pritchard
Sedgwick
Horizon Channel
Mukluk Channel
ALEUTIAN ABYSSAL PLAIN
TUFTS ABYSSAL PLAIN
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French Frigate
Necker
Nihoa
Kauai
Oahu
Molokai
Maui
Lanai
Hawaii
Honolulu
Islands
PIONEER

Volcanism in Hawaii

Edited by Robert W. Decker, Thomas L. Wright, *and* Peter H. Stauffer

Volume 1

- Physiography, Tectonics, and Submarine Geology
- Geology of the Island of Hawaii
- Petrogenesis and Volcanic Gases

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THE HAWAIIAN-EMPEROR VOLCANIC CHAIN
Part I
Geologic Evolution

By David A. Clague *and* G. Brent Dalrymple

ABSTRACT

The Hawaiian-Emperor volcanic chain stretches nearly 6,000 km across the North Pacific Ocean and consists of at least 107 individual volcanoes with a total volume of about 1 million km^3. The chain is age progressive with still-active volcanoes at the southeast end and 80–75-Ma volcanoes at the northwest end. The bend between the Hawaiian and Emperor Chains reflects a major change in Pacific plate motion at 43.1 ± 1.4 Ma and probably was caused by collision of the Indian subcontinent into Eurasia and the resulting reorganization of oceanic spreading centers and initiation of subduction zones in the western Pacific. The volcanoes of the chain were erupted onto the floor of the Pacific Ocean without regard for the age or preexisting structure of the ocean crust.

Hawaiian volcanoes erupt lava of distinct chemical compositions during four major stages in their evolution and growth. The earliest stage is a submarine alkalic preshield stage, which is followed by the tholeiitic shield stage. The shield stage probably accounts for >95 percent of the volume of each volcano. The shield stage is followed by an alkalic postshield stage during which a thin cap of alkalic basalt and associated differentiated lava covers the tholeiitic shield. After several million years of erosion, alkalic rejuvenated-stage lava erupts from isolated vents. An individual volcano may become extinct before the sequence is complete. The alkalic preshield stage is only known from recent study of Loihi Seamount. Lava from later eruptive stages has been identified from numerous submerged volcanoes located west of the principal Hawaiian Islands.

Volcanic propagation rates along the chain are 9.2 ± 0.3 cm/yr for the Hawaiian Chain and 7.2 ± 1.1 cm/yr for the Emperor Chain. A best fit through all the age data for both chains gives 8.6 ± 0.2 cm/yr. Alkalic rejuvenated-stage lava erupts on an older shield during the formation of a new large shield volcano 190 ± 30 km to the east. The duration of the quiescent period preceding eruption of rejuvenated-stage lava decreases systematically from 2.5 m.y. on Niihau to <0.4 m.y. at Haleakala, reflecting an increase in the rate of volcanic propagation during the last few million years. Rejuvenated-stage lava is generated during the rapid change from subsidence to uplift as the volcanoes override a flexural arch created by loading the new shield volcano on the ocean lithosphere.

Paleomagnetic data indicate that the Hawaiian hot spot has remained fixed during the last 40 m.y., but prior to that time the hot spot was apparently located at a more northerly latitude. The most reliable data suggest about 7° of southward movement of the hot spot between 65 and 40 Ma.

The numerous hypotheses to explain the mechanism of the hot spot fall into four types: propagating fracture hypotheses, thermal or chemical convection hypotheses, shear melting hypotheses, and heat injection hypotheses. A successful hypothesis must explain the propagation of volcanism along the chain, the near-fixity of the hot spot, the chemistry and timing of the eruptions from individual volcanoes, and the detailed geometry of volcanism. None of the geophysical hypotheses proposed to date are fully satisfactory. However, the existence of the Hawaiian swell suggests that hot spots are indeed hot. In addition, both geophysical and geochemical hypotheses suggest that primitive undegassed mantle material ascends beneath Hawaii. Petrologic models suggest that this primitive material reacts with the ocean lithosphere to produce the compositional range of Hawaiian lava.

INTRODUCTION

The Hawaiian Islands; the seamounts, banks, and islands of the Hawaiian Ridge; and the chain of Emperor Seamounts form an array of shield volcanoes that stretches nearly 6,000 km across the north Pacific Ocean (fig. 1.1). This unique geologic feature consists of more than 107 individual volcanoes with a combined volume slightly greater than 1 million km^3 (Bargar and Jackson, 1974). The chain is age progressive with still-active volcanoes at the southeast end whereas those at the northwest end have ages of about 75–80 Ma. The volcanic ridge is surrounded by a symmetrical depression, the Hawaiian Deep, as much as 0.7 km deeper than the adjacent ocean floor (Hamilton, 1957). The Hawaiian Deep is in turn surrounded by the broad Hawaiian Arch.

At the southeast end of the chain lie the eight principal Hawaiian Islands. Place names for the islands and seamounts in the chain are shown in figure 1.1 (see also table 1.2). The Island of Hawaii includes the active volcanoes of Mauna Loa, which erupted in 1984, and Kilauea, which erupted in 1986. Loihi Seamount, located about 30 km off the southeast coast of Hawaii, is also active and considered to be an embryonic Hawaiian volcano (Malahoff, chapter 6; Moore and others, 1979, 1982). Hualalai Volcano on Hawaii and Haleakala Volcano on Maui have erupted in historical times. Between Niihau and Kure Island only a few of the volcanoes rise above the sea as small volcanic islets and coral atolls. Beyond Kure the volcanoes are entirely submerged beneath the sea. Approximately 3,450 km northwest of Kilauea, the Hawaiian Chain bends sharply to the north and becomes the Emperor Seamounts, which continue northward another 2,300 km.

It is now clear that this remarkable feature was formed during the past 70 m.y. or so as the Pacific lithospheric plate moved north and then west relative to a melting anomaly, called the Hawaiian hot spot, located in the asthenosphere. According to this hot-spot hypothesis, a trail of volcanoes was formed and left on the ocean

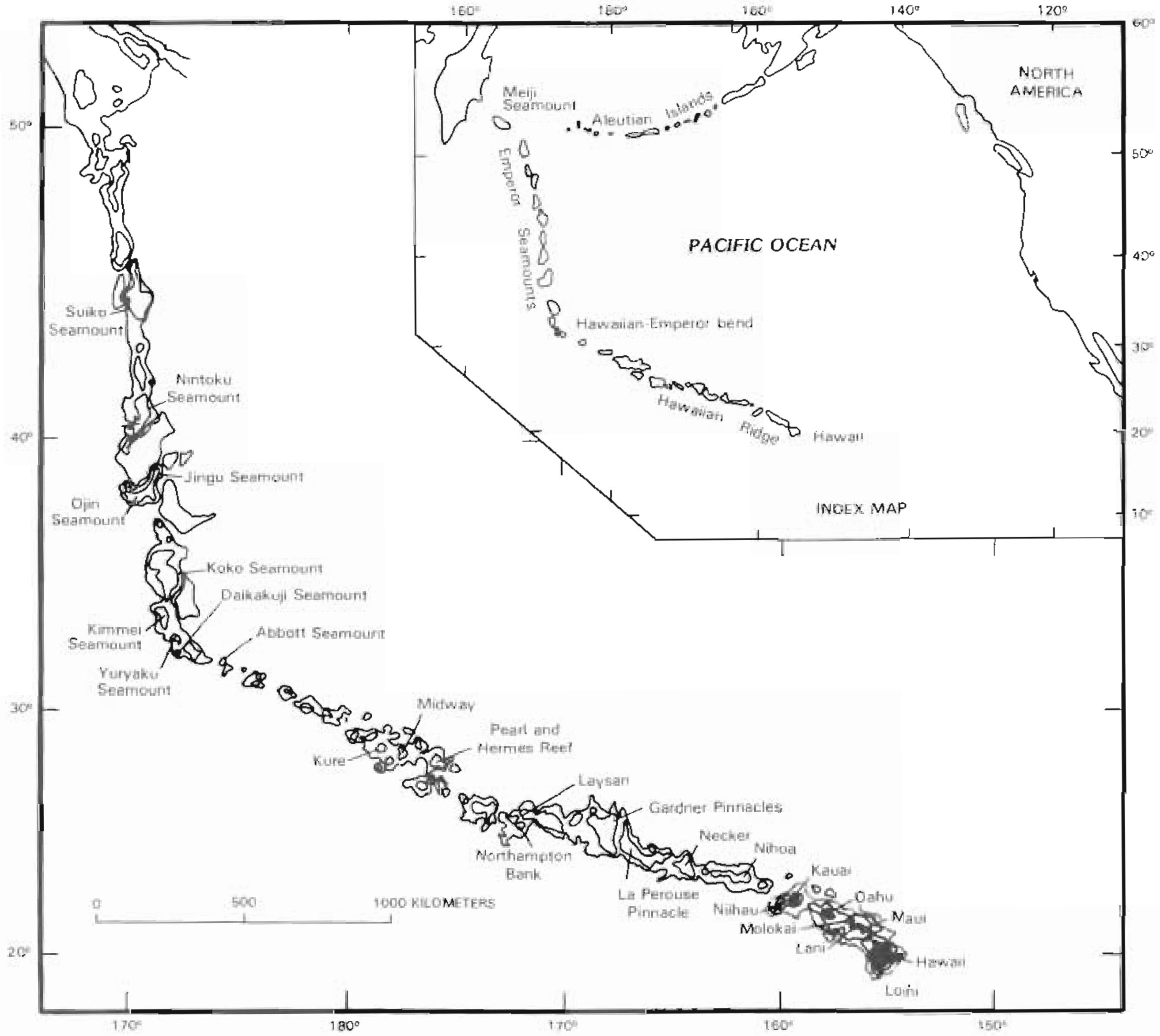

FIGURE 1.1.—Bathymetry of Hawaiian-Emperor volcanic chain modified from Chase and others (1970). Contours at 1-km and 2-km depths shown in area of the chain only. Inset shows location of chain (outlined by 2-km depth contour) in central North Pacific.

floor as each volcano was progressively cut off from its source of lava and a new volcano was born behind it.

Wilson (1963a, c) was the first to propose that the Hawaiian Islands and other parallel volcanic chains in the Pacific were formed by movement of the sea floor over sources of lava in the asthenosphere. Although the Emperor Chain was recognized as a northward continuation of the Hawaiian Chain by Bezrukov and Udintsev (1955) shortly after the Emperor Seamounts were first described by Tayama (1952) and Dietz (1954), Wilson confined his hypothesis to the volcanoes of the Hawaiian Islands and the Hawaiian Ridge. Christofferson (1968), who also coined the term "hot spot," extended Wilson's idea to include the Emperor Seamounts and suggested that the Hawaiian-Emperor bend represents a major change in the direction of sea-floor spreading from northward to westward. Morgan (1972a, b) proposed that the Hawaiian and other hot spots are thermal plumes of material rising from the deep mantle and that the worldwide system of hot spots constitutes a reference frame that is fixed relative to Earth's spin axis.

Although experimental testing of the various hypotheses proposed to explain hot spots has so far proven unproductive, the hot-spot hypothesis has several important corollaries that can and have been tested to varying degrees. Foremost among these is that the volcanoes should become progressively older to the west and north as a function of distance from the hot spot. This progressive aging should be measurable with radiometric methods and also should be evident in the degree of erosion, subsidence, and geological evolution of the volcanoes along the chain. A second important corollary is that the latitude of formation of the volcanoes, as recorded in the magnetization of their lava flows, should reflect the present latitude of the hot spot rather than the present latitude of the volcanoes. Third, because the active mechanism is beneath the lithosphere, the Hawaiian-Emperor Chain should show no relation to the structure of the sea floor. Finally, the volcanic rocks of the volcanoes should be similar in both chemistry and sequence of eruption for each volcano along the chain, or should change in a systematic and coherent way.

In this paper we describe the Hawaiian-Emperor volcanic chain and those individual volcanoes that have been sampled and studied. We review the evidence that indicates that all of the corollaries mentioned above are true and, therefore, that the hot-spot hypothesis is a viable explanation of the origin of the chain. We will also describe the various hypotheses that have been proposed to explain the hot-spot mechanism and discuss their strengths and weaknesses.

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STRUCTURE AND AGE OF THE UNDERLYING CRUST

The volcanoes of the Hawaiian-Emperor Chain were formed by eruption of lava onto the floor of the Pacific Ocean without regard for the age or preexisting structure of the ocean crust, or for the presence of preexisting volcanoes. The precise age of the ocean crust beneath much of the chain is poorly known because of the paucity of magnetic anomalies in the area (fig. 1.2). The Hawaiian Islands and Ridge east of about Midway Island lie on crust older than anomaly 34 but younger than anomaly M0. In a general way, both the Hawaiian seamounts and the underlying crust increase in age to the west so that the age of the crust beneath each volcano at the time it was built was between 80 and 90 m.y. (fig. 1.3). Volcanoes between Midway and the Hawaiian-Emperor bend and in the Emperor Seamounts south of Jingu Seamount are all built on crust whose age is between that of anomalies M0 and M3. Because the seamounts increase in age to the northwest but the underlying crust is roughly the same age, the age of the crust when the overlying volcano was built decreases systematically from about 80 m.y. at the bend to about 55 m.y. at Jingu Seamount. North of Jingu Seamount the age of the crust is not known, but plate reconstructions imply decreasing crustal ages to the north (Scientific Party DSDP 55, 1978; Byrne, 1979).

Northward from Jingu Seamount, we estimate that the crustal age at Suiko was roughly 40 m.y. and at the northernmost seamount, Meiji, was <20 m.y. when those volcanoes formed. If this extrapolation is extended beyond Meiji Seamount to hypothetical seamounts we presume existed once but which have been subducted or accreted in the Kuril Trench, we conclude that the Hawaiian hot spot was located, and perhaps originated, beneath the Kula-Pacific spreading axis at about 100–90 Ma.

Preexisting structures in and on the underlying crust appear to have had little or no influence on the formation of the Hawaiian-Emperor Chain (fig. 1.2). Several fracture zones, including the Mendocino, Murray, and Molokai, cross the chain, but none appears to have greatly affected the orientation of the chain, the rate of propagation of volcanism, or the volume of eruptive products. Likewise, the chain has overridden at least one Late Cretaceous seamount, again without obviously affecting the orientation, rate of propagation of volcanism, or the volumes of eruptive products (Clague and Dalrymple, 1975).

ERUPTIVE SEQUENCE

Hawaiian volcanoes erupt lava of distinct chemical compositions during four different stages in their evolution and growth (table 1.1). The three later stages are well studied and documented (Stearns, 1940a, b, c; Macdonald and Katsura, 1964; Macdonald, 1968), but the first (preshield) stage, which includes the early phase of the submarine history of the volcano, has only been examined recently (Moore and others, 1979, 1982).

The tholeiitic eruptive stage includes a long period of submarine eruption that forms a volcanic edifice with steep slopes and a subaerial eruptive phase that forms the shield-shaped volcano (Peterson and Moore, chapter 7). In this paper we refer to this entire stage of tholeiitic volcanism as the shield stage. In the shield stage, tholeiitic basalt flows construct the main volcanic edifice in the relatively short span of perhaps 1 m.y. or less (Jackson and others, 1972). Wright and others (1979) independently propose 200,000 yr as the duration of tholeiitic volcanism. Most of the mass of an individual volcano (95–98 percent) is formed from these voluminous eruptions. The shield stage usually includes caldera collapse and eruption of caldera-filling tholeiitic basalt. During the next stage, the alkalic postshield stage, alkalic basalt also may fill the caldera and form a thin cap of alkalic basalt and associated differentiated lava that covers the main shield. This alkalic lava accounts for less than 1 percent of the total volume of the volcano. After as much as a few million years of volcanic quiescence and erosion, very small amounts of SiO_2-poor lava may erupt from isolated vents; this stage is commonly called the posterosional stage; we refer to it here as the alkalic rejuvenated stage. An individual volcano may become extinct before this eruptive cycle is complete, but the general sequence is typical of the well-studied Hawaiian volcanoes (table 1.2). Some of these ideas are more than half a century old. Cross (1915) recognized that each of the Hawaiian volcanoes built a shield of lava, comparable to Kilauea flows, during a period of frequent voluminous eruptions. He also noted that this period was followed by a period of erosion and declining activity that produced cinder cones

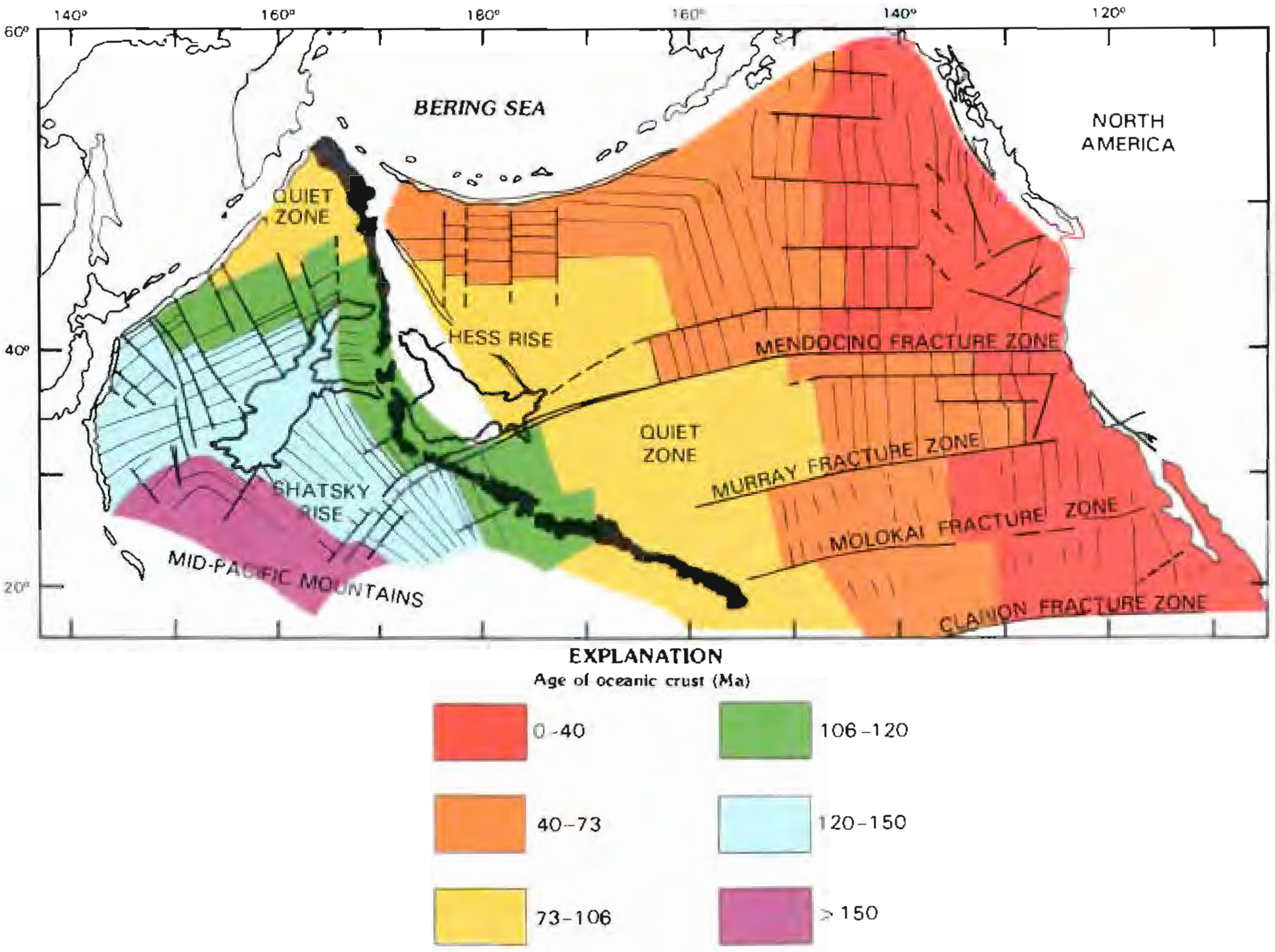

FIGURE 1.2.—Magnetic anomalies and structure of ocean floor crust in North Pacific modified from Hilde and others (1976). Hawaiian-Emperor Chain (black) crosscuts preexisting fracture zones and Mesozoic magnetic-anomaly sequence.

and small flows of lava richer in SiO_2 and FeO (these are the hawaiite and mugearite that characterize the alkalic postshield stage). S. Powers (1920) noted that eruptive centers of nepheline basalt on Kauai, Oahu, Molokai, and Maui were active long after the main volcano became quiet; he appears to have been the first to associate nepheline basalt with late-stage eruptions following an erosional hiatus.

New insight into the preshield stage has come from recent studies of Loihi Seamount, a small submarine volcano located about 30 km off the southeast coast of Hawaii. Its location, small size, seismic activity, and fresh, glassy lava all indicate that Loihi is an active volcano and the youngest in the Hawaiian-Emperor Chain. Some of the older lava samples recovered from Loihi Seamount are alkalic basalt and basanite, whereas the youngest lava samples recovered are tholeiitic and transitional basalt. This observation led Moore and others (1982) to conclude that Loihi Seamount, and perhaps all Hawaiian volcanoes, initially erupt alkalic basalt. Later, the bulk of the shield is built of tholeiitic basalt, but during declining activity the magma compositions revert to alkalic basalt. The alkalic preshield stage, like the alkalic postshield stage, produces only small volumes of lava, probably totaling less than a few percent of the volcano.

We have omitted the main caldera-collapse stage of Stearns (1966) from the eruption sequence because it can occur either during the shield stage or near the beginning of the alkalic postshield stage. The lava erupted may therefore be tholeiitic or alkalic basalt, or of both types.

GEOLOGY OF THE HAWAIIAN ISLANDS

Descriptions of volcanoes and their eruptions were made by nearly all the earliest visitors to the Hawaiian Islands. Descriptions of particular note are those of William Ellis (1823), George, Lord Byron (1826), Joseph Goodrich (1826, 1834), and Titus Coan

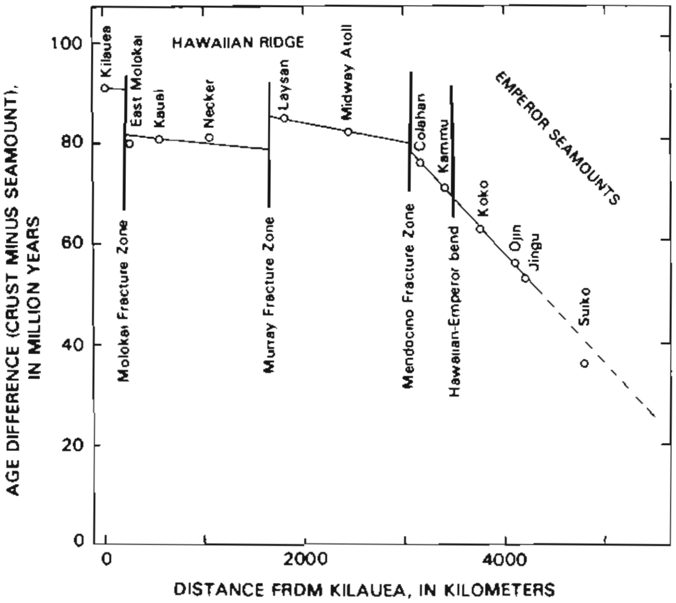

FIGURE 1.3.—Age of oceanic crust when overlying volcano formed, as a function of distance from Kilauea, for selected volcanoes in Hawaiian-Emperor Chain. Note offsets at fracture zones. Along Hawaiian Ridge both crust and volcanoes increase in age to west so crustal age when volcanoes formed is roughly constant. On the other hand, Emperor Seamounts increase in age to north but crust decreases in age; thus age of crust when seamounts formed decreases from roughly 75 Ma at the bend to less than 40 Ma at Suiko Seamount.

TABLE 1.1.—*Hawaiian eruptive products*

Eruptive stage	Rock types	Eruption rate	Volume (percent)
Rejuvenated —	alkalic basalt basanite nephelinite nepheline melilitite	Very low	<1
Postshield ---	alkalic basalt transitional basalt ankaramite hawaiite mugearite benmoreite trachyte phonolite	Low	~1
Shield -------	tholeiitic basalt olivine tholeiitic basalt picritic tholeiitic basalt icelandite (rare) rhyodacite (rare) [1]alkalic basalt (?)	High	95-98
Preshield ----	basanite alkalic basalt transitional basalt [1]tholeiitic basalt (?)	Low	~3

[1] Wright and Helz (chapter 23) suggest that the shield stage may include rare intercalated alkalic basalt and that the preshield stage includes tholeiitic basalt. We suspect that tholeiitic and alkalic basalt occur intercalated during the transitions from preshield to shield stage and from shield stage to postshield stage but that during the main shield stage only tholeiitic lava is erupted.

(1840 and other letters until 1882). Many of their letters describing the volcanoes were published in the American Journal of Science. Goodrich, in particular, provided detailed descriptions of the volcanoes on the Island of Hawaii. None of the earliest descriptions however, included information about the mineralogy or petrology of the lava.

The United States Exploring Expedition visited Hawaii in 1840–41. The commander of the expedition published a narrative (Wilkes, 1845) containing descriptions of caldera activity at Kilauea and new maps of both Kilauea and Mauna Loa calderas. James D. Dana, the geologist of the expedition, published a detailed report on the geology of the areas visited by the expedition (Dana, 1849). This report contains descriptions of lava flows including their mineralogy and flow morphology, in addition to numerous other observations on the active and inactive volcanoes that make up the islands. Later reports by Dutton (1884), J.D. Dana (1887, 1888, 1889), Green (1887), and Brigham (1909) added details on eruptions and expanded the geologic observations to other islands.

E.S. Dana (1877), Cross (1904), and Hitchcock (1911) presented detailed petrographic descriptions of lava from the islands. Daly (1911) and Cross (1915) described the mineralogy and petrology of Hawaiian lava flows at the time the Hawaiian Volcano Observatory was established, and Jagger (1917) described activity in Halemaumau lava lake. The paper by Cross (1915) is a milestone because it added detailed descriptions and chemical analyses of rocks from Hawaiian volcanoes other than Kilauea and Mauna Loa.

More detailed petrographic descriptions of lava from the islands were published by S. Powers (1920). Soon afterward, papers appeared by Washington (1923a, b, c) and Washington and Keyes (1926, 1928) with detailed accounts of the geology and petrology, new high-quality chemical analyses of lava from Hawaii and Maui, and a classification of Hawaiian volcanic rocks. Palmer (1927, 1936) added geologic descriptions and petrography of lava from Kaula and Lehua Islands, both of which are tuff cones of the alkalic rejuvenated stage. Lehua Island is just one of several rejuvenated-stage vents associated with Niihau, whereas Kaula Island sits atop a completely submerged shield.

These early, mainly descriptive and reconnaissance studies were superseded by detailed mapping of the islands beginning in the 1930's. H.T. Stearns and his coworkers, in a remarkable series of bulletins published by the Hawaii Division of Hydrography, published geologic maps and descriptions of Oahu (Stearns and Vaksvik, 1935; Stearns, 1939, 1940b), Lanai and Kahoolawe (Stearns, 1940c), Maui (Stearns and Macdonald, 1942), Hawaii (Stearns and Macdonald, 1946), Niihau (Stearns, 1947), and Molokai (Stearns and Macdonald, 1947). The bulletin on Kauai by Macdonald and others (1960) completed the monumental mapping job begun by Stearns; though Stearns did not coauthor the report, he did much of the mapping and is an author of the map. These maps and bulletins provide the geologic framework for all

TABLE 1.2.—*Eruptive stages represented on volcanoes of the Hawaiian-Emperor Chain*

[Volcano numbers from Bargar and Jackson (1974); numbers 0 and 65A added for consistency. Presence of stages: M, major unit; R, rare or of small volume; X, present but extent unknown; A, known to be absent; -, unknown. (T), transitional lava probably erupted during late shield stage or caldera-collapse phase of that stage. For volcanoes from Kilauea through Necker, data from detailed mapping and sampling; for remaining volcanoes, primarily from dredge and drill samples]

Volcano		Eruptive Stages			
Number	Name	Preshield (alkalic)	Shield (tholeiitic)	Postshield (alkalic)	Rejuvenated (alkalic)
Hawaiian Islands					
0	Loihi	M	M	-	-
1	Kilauea	-	M	A	A
2	Mauna Loa	-	M	A	A
3	Mauna Kea	-	M	M	A
4	Hualalai	-	M	M	A
5	Kohala	-	M	M	A
6	East Maui	-	M	M	M
7	Kahoolawe	-	M	R	R
8	West Maui	-	M	R	R
9	Lanai	-	M	A	A
10	East Molokai	-	M	M	R
11	West Molokai	-	M	R	A
12	Koolau	-	M	A	M
13	Waianae	-	M	M	R
14	Kauai	-	M	R	M
15	Niihau	-	M	R	M
15A	Kaula	-	X	X	X
Northwestern Hawaiian Islands and Hawaiian Ridge					
17	Nihoa	-	M	-	-
19	(Unnamed Seamount)	-	X(T)	-	-
20	(Unnamed Seamount)	-	X	-	X
21	(Unnamed Seamount)	-	X	-	-
23	Necker	-	M	X	X
26	La Perouse Pinnacles	-	X	-	-
28	Brooks Bank	-	X(T)	X	-
29	St. Rogatien Bank	-	-	X	-
30	Gardner Pinnacles	-	X	X	-
36	Laysan	-	-	X	-
37	Northampton Bank	-	X	-	-
39	Pioneer Bank	-	X	-	-
50	Pearl and Hermes Reef	-	-	X	-
51	Ladd Bank	-	-	-	X
52	Midway	-	M	X	-
53	Nero Bank	-	X	-	-
57	(Unnamed Seamount)	-	-	X	-
63	(Unnamed Seamount)	-	-	-	X
65	Colahan	-	X	-	X
65A	Abbott	-	X(T)	-	-
Emperor Seamounts					
67	Daikakuji	-	X	-	-
69	Yuryaku	-	X	X	-
72	Kimmei	-	-	X	-
74	Koko (southern)	-	X	M	-
76	Koko (northwest)	-	X	-	-
81	Ojin	-	X	X	-
83	Jingu	-	-	X	-
86	Nintoku	-	-	X	-
90	Suiko (southern)	-	-	X	-
91	Suiko (central)	-	M	X	-
108	Meiji	-	M	-	-

subsequent studies of the islands and can also be used to put many of the earlier descriptions into a broader geological context. A number of derivative publications include summaries of the geology of the islands by Stearns (1946, 1966), an overview of the petrography of lava from the islands by Macdonald (1949), and a summary of the geology of the Hawaiian Islands by Macdonald and others (1983). The brief geologic summaries in appendix 1.1 have largely been extracted from the above publications. Additional unpublished observations by ourselves are included for Hualalai, East and West Molokai, Koolau, Kauai, and Niihau.

The maps of Stearns and coworkers separate rejuvenated-stage lava from earlier lava, but do not subdivide shield and postshield lava on the basis of chemical composition. The eruptive stages that are known to occur in each of the volcanoes of the Hawaiian Islands are summarized in table 1.2. Evidence for the alkalic preshield stage exists only at Loihi Seamount. If this stage is present in all Hawaiian volcanoes, it is completely buried by later, shield-stage tholeiitic lava. The tholeiitic shield stage is known to form the major portion of the subaerial and, we assume, the submarine part of each volcano. On the main islands, only Hualalai Volcano and Kaula Island do not have subaerial exposures of tholeiitic lava. Alkalic lava of the alkalic postshield stage occurs relatively late in the eruptive sequence and has not yet developed on Loihi Seamount or Kilauea and Mauna Loa Volcanoes. To the northwest of there it occurs on all volcanoes except Lanai and Koolau, although the volumes present on Kauai, Niihau, Kahoolawe, and West Molokai are small. Some volcanoes have predominantly mugearite, whereas others have predominantly hawaiite; these are called Kohala type and Haleakala type, respectively, by Macdonald and Katsura (1962). Wright and Clague (in press) propose two additional types: a Hualalai type with a bimodal trachyte-alkalic basalt lava distribution and a Koolau type with little or no alkalic postshield lava present.

Hawaiian volcanoes commonly have summit calderas and elongate curved rift zones from which much of the lava issues. Summit calderas exist on Loihi Seamount (Malahoff, chapter 6; Malahoff and others, 1982), Kilauea, and Mauna Loa. Each of these calderas is connected to two prominent rift zones. Not all Hawaiian volcanoes, however, had a summit caldera. West Molokai Volcano, in particular, shows no evidence of ever having had a caldera. Flat-lying lava ponded inside a caldera is not exposed on Hualalai, Mauna Kea, Kohala, or Niihau, but former calderas are inferred at those volcanoes from geophysical data (see Macdonald and others, 1983).

The formation and structure of the rift zones have been examined in an elegant paper by Fiske and Jackson (1972), who concluded that the orientation of the rift zones reflects local gravitational stresses within the volcanoes. Isolated shields such as Kauai and West Molokai had nearly symmetrical stress fields represented by generally radial dikes and thus have only poorly defined rift zones. The rift zones of these isolated volcanoes tend to align parallel to the orientation of the chain, suggesting the influence of a more regional stress field that also controls the orientation of the chain. In contrast, the rift zones of the other volcanoes tend to be aligned parallel to the flanks of the preexisting shields against which they abut.

GEOLOGY OF THE HAWAIIAN RIDGE

The Northwestern Hawaiian Islands were the focus of all geologic investigations along the Hawaiian Ridge west of Kauai until oceanographic techniques were applied to the area in the 1950's. Geological descriptions of the leeward islands include those of S. Powers (1920) for Nihoa and Necker Islands, and Washington and Keyes (1926) and Palmer (1927) for Nihoa, Necker, Gardner Pinnacles, and French Frigates Shoal (LaPerouse Pinnacles). These reports cite earlier sketchy descriptions. Macdonald (1949) reexamined Palmer's samples and added more detailed petrography. The petrology of the basaltic basement of Midway Atoll is described from two drill cores by Macdonald (1969) and Dalrymple and others (1974, 1977), whereas the geology of the site is detailed by Ladd and others (1967, 1969). Paleomagnetic data on flows and dikes from Nihoa and Necker Islands are given by Doell (1972), whereas similar data from the Midway drill core are given by Gromme and Vine (1972).

Marine geologic investigations of the Hawaiian Ridge began with Hamilton's pioneering work in 1957. Much subsequent work has focused on the structure of the oceanic crust in the vicinity of the chain, but few cruises have actually been conducted that dealt mainly with the geology of the Hawaiian Ridge. In the early 1970's, Scripps Institution of Oceanography and the Hawaii Institute of Geophysics conducted cruises to the Hawaiian Ridge. Samples collected by these cruises are described in Clague (1974a, 1974b) and Garcia, Grooms, and Naughton (in press). Subsequent cruises to the area by the Hawaii Institute of Geophysics and the U.S. Geological Survey are cited in appendix 1.1.

Lava samples recovered from the Hawaiian Ridge and Emperor Seamounts are more difficult to assign to volcanic stages because they are recovered by dredging and drilling or are collected from small islets and the field relations are usually unknown or only poorly known. Table 1.2 summarizes the available data from the Hawaiian Ridge. Based on the sequence and volumes of lava in the Hawaiian Islands, we have assumed that tholeiitic basalt always represents the shield stage and that strongly alkalic, SiO_2-poor lava represents the alkalic rejuvenated stage. Differentiated alkalic lava has been assigned to the alkalic postshield stage. Some alkalic basalt occurrences could be assigned to either the alkalic postshield or rejuvenated stages; they have been assigned on the basis of trace-element signatures and mineral chemistry using criteria outlined in a later section of this paper. No lava samples have been assigned to the alkalic preshield stage because we assume that the small volumes of such early lava have been buried by the later voluminous tholeiitic lava of the shield stage.

The samples recovered by dredging are probably not representative of the lava forming the bulk of the individual seamounts, but instead represent the youngest lava types erupted on the volcanoes. This natural sampling bias should result in an overrepresentation of alkalic lava from both the postshield and rejuvenated stages. In addition, selection of recovered samples for further study introduces another bias because the freshest samples are commonly alkalic lava, particularly hawaiite, mugearite, and trachyte. With these biases in mind, it is still possible to note general trends along the entire chain.

Tholeiitic basalt and picritic tholeiitic basalt, similar to those of the shield stage of subaerial Hawaiian volcanoes, have been recovered from 11 seamounts, banks, and islands in the Hawaiian Ridge west of Kauai and Niihau (table 1.2; appendix 1.1). The abundance of tholeiitic basalt from the Hawaiian Ridge implies that these volcanoes are genetically related to the Hawaiian Islands and that the general sequence of Hawaiian volcanism, in which tholeiitic basalt forms a major portion of each volcano, has occurred along the entire Hawaiian Chain.

GEOLOGY OF THE EMPEROR SEAMOUNTS

Little was known of the geology of the Emperor Seamounts until quite recently. The chain was recognized as the continuation of the Hawaiian Ridge by Bezrukov and Udintsev (1955), but not until 1968 were the first samples recovered from Suiko Seamount (Ozima and others, 1970). These samples are dominantly, if not completely, ice-rafted detritus. Subsequent studies included a cruise to the southern part of the chain by Scripps Institution of Oceanography in 1971 (ARIES Leg VII; Davies and others, 1971, 1972), Deep Sea Drilling Project (DSDP) Site 192 on Meiji Seamount (Creager and Scholl, 1973), DSDP Sites 308 and 309 on Koko Seamount (Larson and others, 1975), a cruise by the Hawaii Institute of Geophysics (Dalrymple and Garcia, 1980), a cruise by the U.S. Geological Survey in 1976 that surveyed the sites for Leg 55 of DSDP (Dalrymple and others, 1980a), and Leg 55 DSDP Sites 430, 431, 432, and 433 in the central part of the chain (Jackson and others, 1980). The Scripps Institution of Oceanography cruise ARIES VII in 1971 and the Leg 55 DSDP cruise in 1977 were particularly successful, and most of our knowledge of the Emperor Seamounts is derived from these two cruises.

The petrology of lava samples recovered by these two cruises is described in Clague (1974a) and Kirkpatrick and others (1980), respectively. A detailed seismic interpretation of the carbonate caps of many of the seamounts is given by Greene and others (1980), and overviews of the results of DSDP Leg 55 are given by Jackson and others (1980) and Clague (1981).

Table 1.2 summarizes the available data on eruptive stages represented by samples from the Emperor Seamounts, and details are given in appendix 1.1 for individual volcanoes. We have assumed that tholeiitic basalt represents the shield stage and that alkalic lava postdates the tholeiitic shield stage; only at Ojin and Suiko Seamounts does drilling show that the alkalic lava overlies the tholeiitic flows.

Tholeiitic basalt and picritic tholeiitic basalt similar to those of the shield stage of subaerial Hawaiian volcanoes have been recovered by drilling and dredging from six volcanic edifices in the Emperor Seamounts. The abundance of tholeiitic lava from the Emperor Seamounts is strong evidence that these volcanoes are genetically related to the Hawaiian Islands and Hawaiian Ridge. Likewise, the general eruptive model for the Hawaiian Islands is apparently applicable to the Emperor Seamounts.

Alkalic postshield-stage lava has been recovered by dredging and drilling from nine seamounts in the chain. In general these samples are alkalic basalt, hawaiite, mugearite, and trachyte similar to lava erupted in the Hawaiian Islands, but lava from Koko Seamount includes anorthoclase trachyte and phonolite that are interpreted to have erupted during the alkalic postshield stage (Clague, 1974a). Lava of the rejuvenated alkalic stage has not been identified from any of the Emperor Seamounts.

SUBSIDENCE OF THE VOLCANOES

Charles Darwin (1837, 1842) was the first to suggest that coral atolls might grow on subsiding platforms and that drowned atolls and certain deeply submerged banks with level tops could be explained by subsidence. Hess (1946) recognized that flat-topped submarine peaks, which he named guyots, were drowned islands. He thought that they were volcanic, bare of sediments and coral, and had been planed off by erosion at sea level. He attributed their depth to rising sea level caused by sediment deposition in the oceans. Menard and Dietz (1951) agreed with Hess that submergence was primarily due to a rise in sea level, but they thought that local subsidence might also play a role. Hamilton (1956), in his classic study of the Mid-Pacific Mountains, which included a program of dredging and coring, concluded that those (and other) guyots were formerly basaltic islands that had been wave and stream eroded and on which coral reefs subsequently grew. Their eventual submergence, he thought, was primarily caused by regional subsidence of the sea floor. It is now known that Darwin and Hamilton were basically correct about the steps leading to the formation of guyots, and about the predominant role of subsidence in the process.

The Hawaiian-Emperor volcanic chain is an excellent example of the gradual transformation of volcanic islands to guyots. From southeast to northwest there is a continuous progression from the active volcanoes such as Mauna Loa and Kilauea through the eroded remnants of Niihau, Nihoa, and Necker, through growing atolls like French Frigates Shoal and Midway Islands, to deeply submerged guyots like Ojin and Suiko. The progression can be observed not only along the chain but within the stratigraphy of individual seamounts. Drilling, dredging, and seismic observations have shown conclusively that the atolls and guyots of the chain are capped by carbonate deposits that overlie subaerial lava flows (see, for example, Ladd and others, 1967; Davies and others, 1971, 1972; Greene and others, 1980; Jackson and others, 1980).

The subsidence of Hawaiian volcanoes with time results from thermal aging of the lithosphere and isostatic response to local loading. The depth of the sea floor (and of volcanoes sitting upon it) increases away from spreading ridges because the lithosphere cools, thickens, and subsides as it moves away from the source of heat beneath the ridge (Parsons and Sclater, 1977; Schroeder, 1984). Detrick and Crough (1978) pointed out that the subsidence of many islands and seamounts, including those along the Hawaiian-Emperor Chain, was far in excess of that which could be accounted for by this normal lithospheric aging or by lithospheric loading. They proposed that the lithosphere is thermally reset locally as it passes over a hot spot and that the excess subsidence is largely a consequence of renewed lithospheric aging.

The Hawaiian-Emperor Chain rests on crust of Cretaceous age (circa 120–80 Ma) for which the depth should be about 5.5–5.9 km. The depth near Hawaii, however, is less than 4.5 km (fig. 1.4). The depth increases along the chain to about 5.3 km near the Hawaiian-Emperor bend in a manner consistent with the thermal resetting hypothesis. Thus, the subsidence of Hawaiian volcanoes as they move away from the hot spot is in part a function of their distance from the hot spot, that is, of the reset thermal age of the lithosphere beneath the chain. The volcanoes are passively riding away from the Hawaiian hot spot on cooling and thickening lithosphere that is subsiding at about 0.02 mm/yr.

Superimposed on the effect of crustal aging is subsidence caused by the immense and rapid loading of the lithosphere by the growing volcanoes (Moore, chapter 2). This effect is local, but while the volcano is active the rate of subsidence caused by loading may exceed that from lithospheric aging by more than two orders of magnitude. Moore (1970) found, from a study of tide-gage records in the Hawaiian Islands and on the west coast of North America, that Hilo on the Island of Hawaii has been subsiding at an absolute rate of 4.8 mm/yr since 1946. Recent data on drowned coral reefs near Kealakekua Bay indicate an absolute subsidence rate for the western side of Hawaii of 1.8 to 3+ mm/yr averaged over the past 300,000 yr and also indicate that the rate may have accelerated during that time (Moore and Fornari, 1984). Moore's (1970) tide-gage data also show that absolute subsidence decreases systematically away from the Island of Hawaii, with rates for Maui and Oahu of 1.7 mm/yr and 0 mm/yr, respectively. Some of this decrease in subsidence may be due to compensating uplift as the volcanoes are carried over the Hawaiian Arch, but an analysis of gravity data indicates that there is no appreciable viscous reaction to the seamount loads over time (Watts, 1978). Thus, it is probable that the volcanoes are isostatically compensated within a few million years of their birth, and that thermal aging of the lithosphere is the major cause of subsidence along the chain.

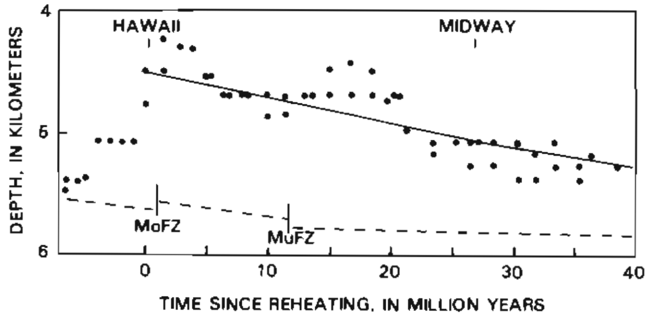

FIGURE 1.4.—Minimum depth to sea-floor swell as a function of time since reheating (or age of volcanoes along chain). Dashed line is predicted depth for normal aging of lithosphere away from spreading ridge. Solid line is predicted depth for thermally reset lithosphere 45 km thick. MoFZ and MuFZ, Molokai and Murray Fracture Zones, respectively. Modified from Detrick and Crough (1978) and Crough (1983).

GEOCHRONOLOGY AND PROPAGATION OF VOLCANISM

EARLY WORK: LEGENDS AND DEGREE OF EROSION

According to Hawaiian legend, the goddess Pele first inhabited Kauai, but then moved southeastward island by island to Kilauea Volcano, where she now resides (Bryan, 1915). The reasoning behind this legend is unknown, but it was probably based in large part on the relative appearance of age of the various volcanoes. Many centuries after this legend originated, J.D. Dana (1849) rendered the first scientific opinion confirming the general age progression implied by the legend.

Dana was not only the first geologist to conclude that the order of extinction of Hawaiian volcanoes was approximately from northwest to southeast, he also recognized that the Hawaiian Chain included the islets, atolls, and banks that stretch for some distance to the northwest of Kauai. Dana saw no reason to think that the volcanoes of the chain did not originate simultaneously: "No facts can be pointed to, which render it even probable that Hawaii is of more recent origin than Kauai" (Dana, 1849, p. 280). Their relative degree of erosion, however, provided ample evidence to indicate their order of extinction: "From Kauai to Mount Loa all may thus have simultaneously commenced their ejections, and have continued in operation during the same epoch till one after another became extinct. Now, the only burning summits out of the thirteen which were once in action from Niihau to Hawaii, are those of Loa and Hualalai: we might say farther that these are all out of a number unknown, which stretched along for fifteen hundred miles, the length of the whole range. This appears to be a correct view of the Hawaiian Islands" (Dana, 1849, p. 280). Subsequent workers agreed with Dana on the general order of extinction (for example, Brigham, 1868; Dutton, 1884; Hillebrand, 1888; Hitchcock, 1911; Cross, 1915; Martin and Pierce, 1915; Wentworth, 1927; Hinds, 1931; Stearns, 1946), although the sequences they proposed invariably differed in detail (table 1.3). Of these various workers only Stearns (1946), who studied the Hawaiian Islands in more detail than any of his predecessors, had the sequence exactly correct as judged by present data.

The idea that the volcanoes of the Hawaiian Chain originated simultaneously and only became extinct progressively seems to have persisted until a few decades ago. Stearns (1946), for example, mentions the lack of evidence to indicate when any of the Hawaiian volcanoes began but shows all of the main shields except Hualalai and Kilauea erupting simultaneously at the end of the Pliocene (Stearns, 1946, p. 97, fig. 25). Two exceptions were Cross (1904) and Wentworth (1927), who thought that the degree of erosion was probably a function of when the volcanoes emerged above the sea as well as of the elapsed time since they ceased to erupt. Cross (1904, p. 518) states: "It appears to me plausible to assume that the earliest eruptions occurred at or near the western limit of this zone (the more than 1000 mile expanse of the island chain), and that in a general way at least, the centers of activity have developed successively farther and farther to the east or southeast, until now the only active loci of eruption are those of Mauna Loa and Kilauea on the island of

TABLE 1.3.—*Early estimates of the order of extinction of the principal Hawaiian volcanoes*

[Criteria used are given beneath each source; volcanoes listed in proposed order of extinction, oldest at top]

Dana (1849) Erosion	Brigham (1868) Erosion	Dana (1888) Erosion	Hillebrand (1888) Floral diversity	Wentworth (1927) Erosion	Hinds (1931) Erosion	Stearns (1946) Erosion and stratigraphy
Kauai Waianae West Maui Koolau Mauna Kea East Maui Mauna Loa	West Kauai, Niihau Waianae East Kauai West Molokai West Maui Kohala Koolau East Molokai Mauna Kea Lanai, Kahoolawe East Maui Hualalai Mauna Loa, Kilauea	Kauai Waianae West Maui Kohala Koolau East Maui Mauna Kea Hualalai Mauna Loa, Kilauea	West Oahu, Kauai Molokai, East Oahu Kohala, West Maui Mauna Kea East Maui Hualalai Mauna Loa, Kilauea	Koolau Kauai East Molokai West Maui Mauna Kea Waianae East Maui Lanai Niihau, West Molokai Kahoolawe Kohala Hualalai, Mauna Loa, Kilauea	Waianae Koolau Niihau Kauai West Molokai East Molokai Lanai West Maui, Kohala Kahoolawe East Maui Mauna Kea Hualalai Mauna Loa, Kilauea	Kauai Waianae Koolau West Molokai East Molokai West Maui, Lanai Kahoolawe East Maui Kohala Mauna Kea Haulalai, Mauna Loa, Kilauea

Hawaii." He specifically noted the difference between his hypothesis and that of Dana.

Estimates of the geologic ages of the Hawaiian volcanoes varied considerably among those early workers willing to hazard a guess on the basis of the meager data then available. Dana (1849) thought it likely that the eruptions commenced as early as early Carboniferous or Silurian time; this estimate was based on the concept that the Earth had cooled from a molten globe producing fissuring and volcanism, the apparent lack of post-Silurian volcanism in the interior of the North American continent, and the presumption that the oceans would cool after the continents. Cross (1904) speculated that the western part of the leeward islands formed in the early part of the Tertiary. Wentworth (1925, 1927) attempted to quantify erosion rates for several of the islands and estimated the extinction ages of some of the volcanoes as follows:

Lanai	0.15 Ma
Kohala	0.22 Ma
Koolau	1.00 Ma
Kauai	2.09 Ma

On the basis of physiographic evidence, Wentworth doubted that any part of the Hawaiian group emerged above sea level before late Tertiary time. Hinds (1931), like Cross (1904), recognized that the atolls and banks of the leeward islands were the remnants of once-larger volcanoes: "The landscapes of the leeward group—the volcanic stacks, the reef limestone and calcareous sand islands rising from submarine platforms, and submerged platforms from which no islands rise, represent the final stages in the destruction of a volcanic archipelago. Such a fate awaits the windward islands unless they be rejuvenated by volcanic or diastrophic forces" (Hinds, 1931, p. 196). He recognized that the amount of erosion and subsidence required to reduce a mammoth Hawaiian volcano to a coral atoll was probably considerable and concluded: "The complete or nearly complete destruction of the Leeward islands suggests that volcanism ceased there well back in the Tertiary, hence the mountains must have risen above the ocean long before, perhaps even in Mesozoic time" (Hinds, 1931, p. 205). On the basis of geomorphic considerations, Stearns (1946) thought that the volcanoes of the main Hawaiian Islands rose above sea level in the Tertiary.

RADIOMETRIC AND FOSSIL AGES

The first radiometric ages for Hawaiian volcanoes were determined by McDougall (1963), who measured ages of 2.8 to 3.6 Ma for his Middle and Upper Waianae Series on Oahu (all K-Ar ages have been converted to the new constants; Steiger and Jaeger, 1977). He also reported an age of 8.6 Ma for what he called the Mauna Kuwale Trachyte of the Lower Waianae Series(?), an age that later proved to be incorrect, probably because of excess argon in the biotite analyzed (Funkhouser and others, 1968). In subsequent studies McDougall and Tarling (1963) and (primarily) McDougall (1964) reported K-Ar ages of lava from 7 of the principal Hawaiian volcanoes and concluded that the ages of the shield stages were approximately:

Kauai	5.8–3.9 Ma
Waianae	3.5–2.8 Ma
Koolau	2.6–2.3 Ma
West Molokai	1.8 Ma
East Molokai	1.5–1.3 Ma
West Maui	1.3–1.15 Ma
East Maui	0.8 Ma
Hawaii (all 5 volcanoes)	<1 Ma

McDougall thus confirmed Stearns' extinction sequence and also suggested that the main shield stage of a Hawaiian volcano essentially was complete before the next volcano rose above the sea.

Since the pioneering work of McDougall, many additional radiometric ages have been determined for the volcanoes of the main islands, and the dating has been extended to the volcanoes of the leeward islands, the western Hawaiian Ridge, and the Emperor Seamounts. In total, there are now reasonably precise radiometric age data for 35 of the volcanoes in the Hawaiian-Emperor Chain (see appendix 1.1). Radiometric ages of two volcanoes on the Hawaiian Ridge are not included in appendix 1.1 because it is probable that the samples are not from Hawaiian volcanoes (Clague and Dalrymple, 1975). These include a minimum age of 71 ± 5 Ma for altered basalt from Wentworth Seamount, 80 km northwest of Midway, and an age of 77.6 ± 1.7 Ma for a sample of rhyolite (probably an erratic, see appendix 1.1) dredged from the northern slope of Necker Island.

In addition to the radiometric age data, there are paleontologic ages for several of the Hawaiian-Emperor volcanoes based on material recovered by dredging and drilling programs. In general, these ages postdate volcanic activity and are consistent with the radiometric data. From southeast to northwest they include (1) an age of 28–31 Ma for late Oligocene nannofossils in volcanogenic sediments at DSDP Site 311 on the archipelagic sediment apron of an unnamed seamount (no. 58 of Bargar and Jackson, 1974) 240 km northwest of Midway (Bukry, 1975); (2) an age of 15–32 Ma (East Indies Tertiary stage Te) for larger foraminifers (Cole, 1969) and smaller foraminifers (Todd and Low, 1970) in reef limestone above basalt in a drill hole at Midway Atoll; (3) an age of 39–41 Ma for dredged late Eocene larger foraminifers from Kammu Seamount (Sachs, quoted in Clague and Jarrard, 1973); (4) an age of 50.5 ± 3.5 Ma for early Eocene coccoliths in volcanogenic sediments cored at DSDP Site 308 atop Koko Seamount (Bukry, 1975); (5) an age of 57–59 Ma for late Paleocene calcareous nannofossils (Takayama, 1980) and pelagic foraminifers (Hagn and others, 1980) in sediments above basalt at DSDP Site 430 on Ojin Seamount; (6) late Paleocene planktonic foraminifers and probable early Eocene benthic foraminifers in sediments above basalt at DSDP Site 432 on Nintoku Seamount (Butt, 1980); (7) an age of 59–61 Ma for middle Paleocene calcareous nannofossils in sediments above basalt at DSDP Site 433 on Suiko Seamount (Takayama, 1980); and (8) an age of 70–73 Ma for lower Maestrichtian nannofossils from sediments above basalt at DSDP Site 192 on Meiji Seamount at the northern end of the Emperor Seamounts (Worsley, 1973). None of these fossil ages is in conflict with the radiometric data.

On the other hand, Menard and others (1962) describe Miocene corals and pelagic foraminifers dredged from a submarine terrace 10 km southwest of Oahu. The authors note the difficulty in assigning an age to these samples and state that the "planktonic foraminifera *Globigerinoides quadralobates* [= *G. trilobus auct.*] *plexus* suggest a lower limit of early Miocene. The upper age limit is less definitive" (Menard and others, 1962, p. 896). Present nomenclature would identify these samples as *Globigerinoides triloba*, which ranges in age from early Miocene to Pleistocene (Kenneth and Srinivasan, 1983). Menard and others (1962) cite as additional evidence of the Miocene age of the sample the 60 percent of extinct coral species in the sample. We conclude that none of these criteria unequivocally supports a Miocene age and no conflict exists between the ages of the reef and that of the underlying volcanic basement of 1.8–2.7 Ma.

Two samples of Eocene terrigenous sediment recovered 250 km east of Hawaii and 100 km south of Kauai (Schreiber, 1969) are also anomalous. These samples were probably derived from volcanoes that predate the Hawaiian Chain, or they may have been reworked from sediment on the sea floor during formation of the Hawaiian volcanoes.

The available radiometric data are summarized in table 1.4 and plotted in figure 1.5 as a function of distance measured from Kilauea Volcano along the Hawaiian-Emperor trend. Because some of the volcanoes are unnamed and some seamounts and islands consist of more than one major volcanic edifice, each dated volcanic center is identified in the table with the number assigned to it by Bargar and Jackson (1974). The exceptions are Abbott Seamount, a small volcano between Colahan and Kammu Seamounts, and Kaula Island, which were not previously numbered and to which we have assigned numbers 65A and 15A, respectively.

As can be seen from figure 1.5, the age data confirm the general age progression along the chain as first suggested by Dana (1849) and required by the hot-spot hypothesis of Wilson (1963a), and they show that the progression is continuous from Kilauea at least to Suiko Seamount, more than half way up the Emperor Seamounts Chain and nearly 5,000 km from the active volcanoes of Mauna Loa and Kilauea. The data also substantiate the hypothesis that the Emperor Seamounts are a continuation of the Hawaiian Chain, as proposed by Christofferson (1968) and Morgan (1972a, b).

RATES OF VOLCANIC PROPAGATION

In order to determine accurately the rate of volcanic propagation along the Hawaiian-Emperor Chain, we would like to know the time that each tholeiitic shield volcano first erupted onto the sea floor, but such data clearly are not obtainable. What is available for the dated volcanoes is one or more radiometric age on lava flows erupted during one or more stage of volcanic activity (see appendix 1.1). In order to calculate propagation rates, therefore, it is necessary to adopt some consistent strategy for selecting the numerical age used to represent the age of each dated volcano. Different authors have approached this problem in different ways. McDougall (1971) used the youngest age of tholeiitic basalt as representing the time of cessation of volcanism for each dated volcano in the principal Hawaiian Islands. In contrast, Jackson and others (1972) and Dalrymple and others (1980b, 1981) used the oldest age for tholeiitic volcanism as the best available approximation of the age of the volcanoes. McDougall (1979) and McDougall and Duncan (1980) adopted yet another approach and used the average age of tholeiitic shield volcanism. For table 1.4, we have chosen the oldest reliable ages for tholeiitic volcanism available, but the choice of which ages to use is probably not critical when considering the data for the chain as a whole. The reason is that the existing data on the rate of formation of Hawaiian volcanoes indicate that the tholeiitic shields are probably built up from the sea floor in as little as 0.5–1.5 m.y. (see summary in Jackson and others, 1972). This amount of time is within the analytical uncertainty of the K-Ar ages at about 20 Ma, or less than one-third of the way along the dated

TABLE 1.4.—*Summary of K-Ar geochronology along the Hawaiian-Emperor volcanic chain*

[Volcano number and distance from Bargar and Jackson (1974) and K.E. Bargar (written commun., 1978). Best K-Ar age is oldest reliable age of tholeiitic basalt, where available; all data converted to new constants $\lambda\varepsilon + \lambda\varepsilon' = 0.581 \times 10^{-10}$/yr, $\lambda\beta = 4.962 \times 10^{-10}$/yr, $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol]

Volcano		Distance from Kilauea along trend of chain (km)	Best K-Ar age (Ma)	Data source	Remarks
Number	Name				
1	Kilauea	0	0-0.4	--	Historical tholeiitic eruptions
3	Mauna Kea	54	0.375±0.05	1	Samples from tholeiitic shield (Hamakua Volcanics)
5	Kohala	100	0.43±0.02	2	Samples from tholeiitic shield (Pololu Basalt)
6	Haleakala	182	0.75±0.04	3	Samples from tholeiitic shield (Honomanu Basalt)
7	Kahoolawe	185	>1.03±0.18	3	Samples from alkalic postshield stage (upper part of Kanapou Volcanics)
8	West Maui	221	1.32±0.04	4	Samples from tholeiitic shield (Wailuku Basalt)
9	Lanai	226	1.28±0.04	5	Samples from tholeiitic shield (Lanai Basalt)
10	East Molokai	256	1.76±0.07	3	Samples from tholeiitic shield (lower member of East Molokai Volcanics)
11	West Molokai	280	1.90±0.06	3	Samples from tholeiitic shield (lower part of West Molokai Volcanics)
12	Koolau	339	2.6±0.1	4,6	Samples from tholeiitic shield (Koolau Basalt)
13	Waianae	374	3.7±0.1	6	Samples from tholeiitic shield (lower member of Waianae Volcanics)
14	Kauai	519	5.1±0.20	7	Sample from tholeiitic shield (Napali Member of Waimea Canyon Basalt)
15	Niihau	565	4.89±0.11	8	Samples from tholeiitic shield (Paniau Basalt)
15A	Kaula	600	4.0±0.2	21	Phonolite from postshield stage (?)
17	Nihoa	780	7.2±0.3	9	Samples from tholeiitic shield
20	Unnamed	913	9.2±0.8	20	Dredged samples of alkalic basalt
23	Necker	1,058	10.3±0.4	9	Samples from tholeiitic shield
26	La Perouse Pinnacles	1,209	12.0±0.4	9	Samples from tholeiitic shield
27	Brooks Bank	1,256	13.0±0.6	20	Dredged samples of hawaiite and alkalic basalt
30	Gardner Pinnacles	1,435	12.3±1.0	20	Dredged samples of alkalic and tholeiitic basalt
36	Laysan	1,818	19.9±0.3	10	Dredged samples of hawaiite and mugearite
37	Northampton Bank	1,841	26.6±2.7	10	Dredged samples of tholeiitic basalt
50	Pearl and Hermes Reef	2,281	20.6±0.5	11	Dredged samples of phonolite, hawaiite, and alkalic basalt
52	Midway	2,432	27.7±0.6	12	Samples of mugearite and hawaiite from conglomerate overlying tholeiitic basalt in drill hole
57	Unnamed	2,600	28.0±0.4	11	Dredged samples of alkalic basalt
63	Unnamed	2,825	27.4±0.5	11	Dredged samples of alkalic basalt
65	Colahan	3,128	38.6±0.3	13	Dredged samples of alkalic basalt
65A	Abbott	3,280	38.7±0.9	13	Dredged samples of tholeiitic (?) basalt
67	Daikakuji	3,493	42.4±2.3	14	Dredged samples of alkalic basalt
69	Yuryaku	3,520	43.4±1.6	11	Dredged samples of alkalic basalt
72	Kimmei	3,668	39.9±1.2	14	Dredged samples of alkalic basalt
74	Koko (southern)	3,758	48.1±0.8	14,15	Dredged samples of alkalic basalt, trachyte, and phonolite
81	Ojin	4,102	55.2±0.7	16	Samples of hawaiite and tholeiitic basalt from DSDP Site 430
83	Jiogu	4,175	55.4±0.9	17	Dredged samples of hawaiite and mugearite
86	Nintoku	4,452	56.2±0.6	16	Samples of alkalic basalt from DSDP Site 432.
90	Suiko (southern)	4,794	59.6±0.6	18,19	Single dredged sample of mugearite
91	Suiko (central)	4,860	64.7±1.1	16	Samples of alkalic and tholeiitic basalt from DSDP Site 433

Data sources:

1. Porter and others (1977)
2. McDougall and Swanson (1972)
3. Naughton and others (1980)
4. McDougall (1964)
5. Bonhommet and others (1977)
6. Doell and Dalrymple (1973)
7. McDougall (1979)
8. G.B. Dalrymple (unpub. data, 1982)
9. Dalrymple and others (1974)
10. Dalrymple and others (1981)
11. Clague and others (1975)
12. Dalrymple and others (1977)
13. Duncan and Clague (1984)
14. Dalrymple and Clague (1976)
15. Clague and Dalrymple (1973)
16. Dalrymple and others (1980a)
17. Dalrymple and Garcia (1980)
18. Saito and Ozima (1975)
19. Saito and Ozima (1977)
20. Garcia and others (1986b)
21. Garcia and others (1986a)

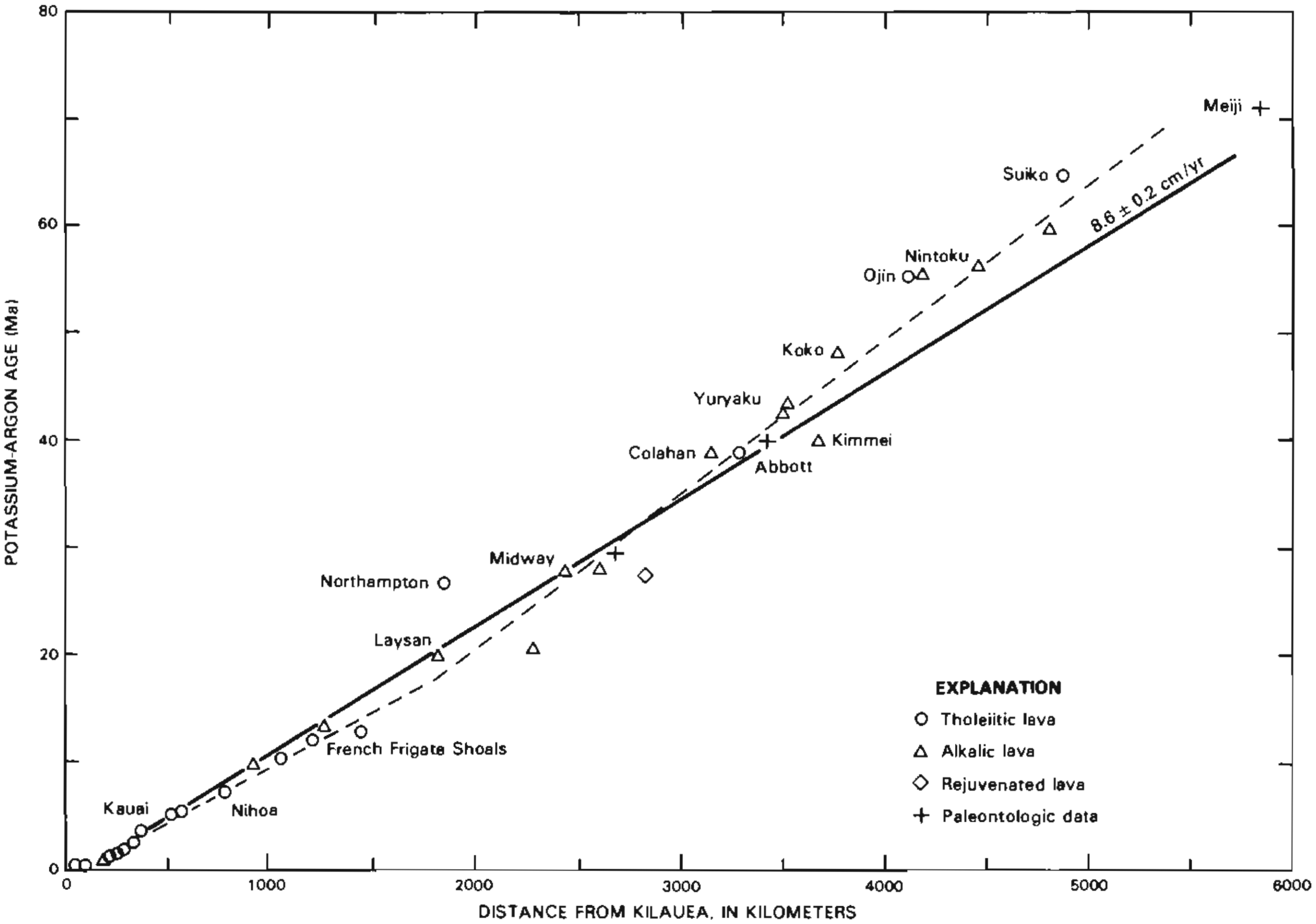

FIGURE 1.5.—Age of volcanoes in Hawaiian-Emperor Chain as a function of distance from Kilauea. Solid line is least-squares cubic fit (York 2) from table 1.5 and represents average rate of propagation of volcanism of 8.6 ± 0.2 cm/yr. Dashed line is two-segment fit using data from Kilauea to Gardner and Laysan to Suiko (table 1.5). Radiometric data from table 1.4, paleontologic data discussed in text.

part of the chain. The question of which ages to use is in any case moot for most of the volcanoes west of Kauai because so few suitable samples have been recovered that there is rarely a choice to make.

A majority of the age data from islands and seamounts west of French Frigates Shoal were obtained on alkalic rocks rather than on tholeiitic basalt. This is because the alkalic rocks, being younger than the tholeiitic basalt, are more likely to be recovered by dredging and drilling and are more resistant to submarine alteration than tholeiitic basalt. This bias toward ages of alkalic lava also probably makes very little difference because the difference between the ages of the postshield alkalic and youngest tholeiitic rocks is only a few hundred thousand years in the Hawaiian Islands (McDougall, 1964, 1969; Funkhouser and others, 1968; McDougall and Swanson, 1972; Doell and Dalrymple, 1973) and, presumably, in the other volcanoes of the Hawaiian-Emperor Chain. For one unnamed volcano on the western Hawaiian Ridge (63 in appendix 1.1 and table 1.4) the only data available are from lava erupted during the alkalic rejuvenated stage. In the principal Hawaiian Islands, lava erupted during the rejuvenated stage may postdate the tholeiitic shield and alkalic postshield stages by more than 4 m.y. (McDougall, 1964; G.B. Dalrymple, unpublished data, 1985), so the main shield of volcano 63 may be several million years older than indicated in table 1.4.

Previously, age-distance data along the Hawaiian-Emperor Chain have been regressed using a simple linear regression of age (dependent variable) on distance (independent variable), either unconstrained (for example, McDougall, 1971, 1979; Jackson and others, 1972; McDougall and Duncan, 1980) or forced through the origin (for example, Dalrymple and others, 1980b, 1981). The resulting volcanic propagation rates for the Hawaiian segment of the chain have ranged from as little as 6 cm/yr (Jackson and others, 1975) to as much as 15 cm/yr (McDougall, 1971; Jackson and others, 1972), although most recent estimates have been between 8 and 10 cm/yr (McDougall, 1979; McDougall and Duncan, 1980;

Dalrymple and others, 1981). Simple linear regression models have the disadvantages that they presume no error in distance and they do not take into account the experimental errors of individual determinations.

We have treated the data in table 1.4 using a two-error cubic fit (York 2), which allows for errors in both age and distance and weights the data accordingly (York, 1969). Errors for the age determinations are straightforward and are either provided in the original references or have been estimated by us from the array of data available on an individual volcano. Jackson and others (1975) estimated the cumulative errors in distance to be about 1.5 km at Kilauea to as much as 20 km near the western end of the Hawaiian Chain. We have interpolated and extrapolated these values to find errors for the distances in table 1.4. The results of both the York 2 regressions and the two simpler regression models for various segments of the Hawaiian-Emperor Chain are given in table 1.5. For the entire chain, the average rate of volcanic propagation is 8.6±0.2 cm/yr with an intersection (that is, theoretical zero time) 89 km northwest of Kilauea using the York 2 regression. The simple regression models yield similar, though slightly lower, values of propagation rate.

Rates of propagation for the Hawaiian segment of the chain, that is, Kilauea through Abbott, have been calculated using both the maximum and minimum ages of tholeiitic volcanism. The results do not vary with model and range from 8.6 to 9.2 cm/yr. For comparison, we have included comparable calculations using the average ages of McDougall (1979). The resulting rates are somewhat higher than the rates calculated from either the maximum or

TABLE 1.5.—*Rates of propagation of volcanism along segments of the Hawaiian-Emperor Chain for several linear-regression models*

[Rates are in centimeters per year. Intercept, in kilometers, and correlation coefficient, r, given in parentheses where relevant. Simple regression is of age on distance, unweighted data; York 2 fit is two-error cubic, weighted data]

Chain segment	Data source	Simple regression		York 2 fit
		Unconstructed	Forced through origin	
Hawaiian-Emperor ---	table 1.4	7.8±0.2 (175, 0.992)	8.2±0.1	8.6±0.2 (89)
Hawaiian -----------	table 1.4 (maximum ages)	8.6±0.3 (102, 0.985)	9.1±0.2	9.2±0.3 (80)
	McDougall, 1979 (average ages)	9.4±0.3 (91, 0.994)	9.9±0.2	11.3±0.1 (3)
	appendix 1.1 (minimum ages)	8.6±0.3 (119, 0.986)	9.1±0.2	9.1±0.3 (97)
Emperor ------------	table 1.4	6.5±0.8	7.9±0.2	7.2±1.1
Kilauea to Gardner -	table 1.4	9.9±0.3 (57, 0.992)	10.6±0.3	9.6±0.4 (73)
Laysan to Suiko ----	table 1.4	6.9±0.4 (0.971)	8.1±0.2	6.8±0.3
Gardner to Waianae -	table 1.4	9.5±0.4 (54, 0.993)	10.1±0.2	10.1±0.8 (9)

minimum data, but the difference is largely a consequence of differences in the data sets, the ones in table 1.4 and appendix 1.1 being more current.

Rates calculated for the Emperor Chain, that is, Daikakuji through Suiko, are markedly lower than for the Hawaiian Chain, ranging from 6.5 to 7.2 cm/yr when not forced through the origin. Separate rates for these two major segments of the chain are only meaningful, however, if there was a rate change at the time of formation of the bend. This hypothesis can be tested by using the linear equations found from the York 2 regressions to predict the age of the bend, which we estimate to be 3,451 km from Kilauea at the position of volcano 68. The predicted ages for the bend are 36.7 Ma and and 43.0 Ma for the Hawaiian and Emperor segments, respectively. The Hawaiian prediction, which is similar to the value of 37.8 Ma found by McDougall (1979), differs significantly from the measured bend age of 43.1 ± 1.4 Ma as determined from the ages of Daikakuji and Yuryaku Seamounts. This suggests that if there was a significant change in volcanic propagation rate it did not occur at bend time, but some time after, a conclusion also reached by Epp (1978).

For some time, it has been apparent to us that a change in rate near or before the time of formation of Midway is consistent with the available data (Dalrymple and others, 1980b). For example, the fits of the data for the chain segments Kilauea-Gardner and Laysan-Suiko are slightly better than the fits for the Hawaiian and Emperor segments (table 1.5; fig. 1.5). The two former lines intersect near Gardner Pinnacles at an age of about 18 Ma. Epp (1978) concluded that a rate change occurred around 20–25 Ma. We have tried various ways to determine the most likely time for a change in the rate of volcanic propagation, including correlation with eruption volumes along the chain (see section below on eruption rates) and age-predictive models for the central parts of the chain, but we are not convinced that the results are meaningful. We can only conclude that the data imply, hut do not require, a change of rate sometime after the formation of the Hawaiian-Emperor bend and before or near the time of formation of Laysan Volcano.

In addition to the possibility of a major change in the volcanic propagation rate, as discussed above, there are also indications of short-term departures from linearity. Short-term changes in the volcanic propagation rate were first proposed by Jackson and others (1972) to explain the apparent acceleration of propagation during the past 5 m.y. or so. They did not suggest that short-term variations in propagation rate reflected variations in relative motion of hot spot and plate. Shaw (1973) and Walcott (1976) proposed thermal feedback mechanisms to account for such variations without varying the relative rate of motion between the hot spot and the Pacific plate (see section below on models). Nonlinear models have been disputed by McDougall (1979) and McDougall and Duncan (1980), who argue that linear regressions fit the Hawaiian data so well that no other model needs to be considered.

It seems obvious to us from the geometry alone, however, that the volcanic propagation rates must be nonlinear in detail. If this were not so, then either the volcanism would have formed a ridge rather than individual volcanoes, or the volcanoes in the chain would be spaced in proportion to their ages along a single line. Neither is the case; the volcanoes are irregularly spaced within a band some 200–300 km wide, indicating clearly that volcanic propagation is irregular.

Although some of the irregularities in the age-distance data no doubt reflect dating errors and differences in the stage of volcanism sampled, some of the deviations appear to be larger than can reasonably be attributed to these causes. For example, the ages of Laysan and Northampton Bank should differ by only about 0.3 m.y. rather than the 6.7 m.y. indicated by their measured ages. A similar discrepancy occurs in the ages of volcanoes near the bend (table 1.4; fig. 1.5). There are also volcanoes in the chain that appear to have been active simultaneously even though they were separated by distances of hundreds of kilometers. Examples include Laysan, and Pearl and Hermes, as well as Midway and Northampton. Indeed, Mauna Loa, Kilauea, and Loihi are currently active, erupting tholeiitic basalt, and are separated by more than 80 km.

The primary reason that Jackson and others (1972) suggested short-term nonlinearities in propagation rates was the pronounced curvature in the age-distance data from the volcanoes of the principal Hawaiian Islands. When plotted as a function of distance from Kilauea, the ages for these volcanoes clearly indicate an acceleration of volcanic propagation over the past 5 m.y. (Jackson and others, 1972). This curvature is also one reason that virtually all regressions intersect the distance axis northwest of Kilauea (table 1.5) and predict a negative age for that volcano. McDougall (1979) has argued that the curvature is caused by a bias toward young ages for the less eroded volcanoes, but this cannot be so. Even though Kohala Mountain is relatively uneroded, it is deeply incised on the windward side by several canyons whose floors are near sea level, and it is unlikely that further erosion will expose lava significantly older than is now exposed. In addition, the rapid subsidence of Hawaii (Moore, 1970) may carry the oldest subaerial lava flows below sea level before they can be exposed by erosion. Similar arguments can be made for West Maui, Lanai, Kahoolawe, East Molokai, and Koolau Volcanoes, where lava deep within the subaerial part of the tholeiitic shield has been exposed by marine or stream erosion or by faulting.

We have plotted the known age range for tholeiitic shield, alkalic postshield, and alkalic rejuvenated-stage volcanism for the principal Hawaiian volcanoes in figure 1.6, from which the acceleration of volcanic propagation over the past 3–5 m.y. is evident. It is also clear from this figure that the curvature in the age-distance data is not a function of which eruption stage, tholeiitic shield or alkalic postshield, is chosen to represent the age of the volcanoes. Furthermore, a bias toward younger ages for the less eroded volcanoes, taken to include Kilauea through Haleakala, cannot produce the curvature because older ages for these volcanoes would exaggerate, not lessen, the apparent acceleration. Thus, the acceleration of volcanic propagation in the principal islands, as proposed by Jackson and others (1972), appears to us to be real.

While the overall rate of propagation of volcanism along the chain (or at least major segments of it) may be linear and reflect the relative motion between the Pacific plate and the Hawaiian hot spot, there also appears to be ample justification for retaining nonlinear

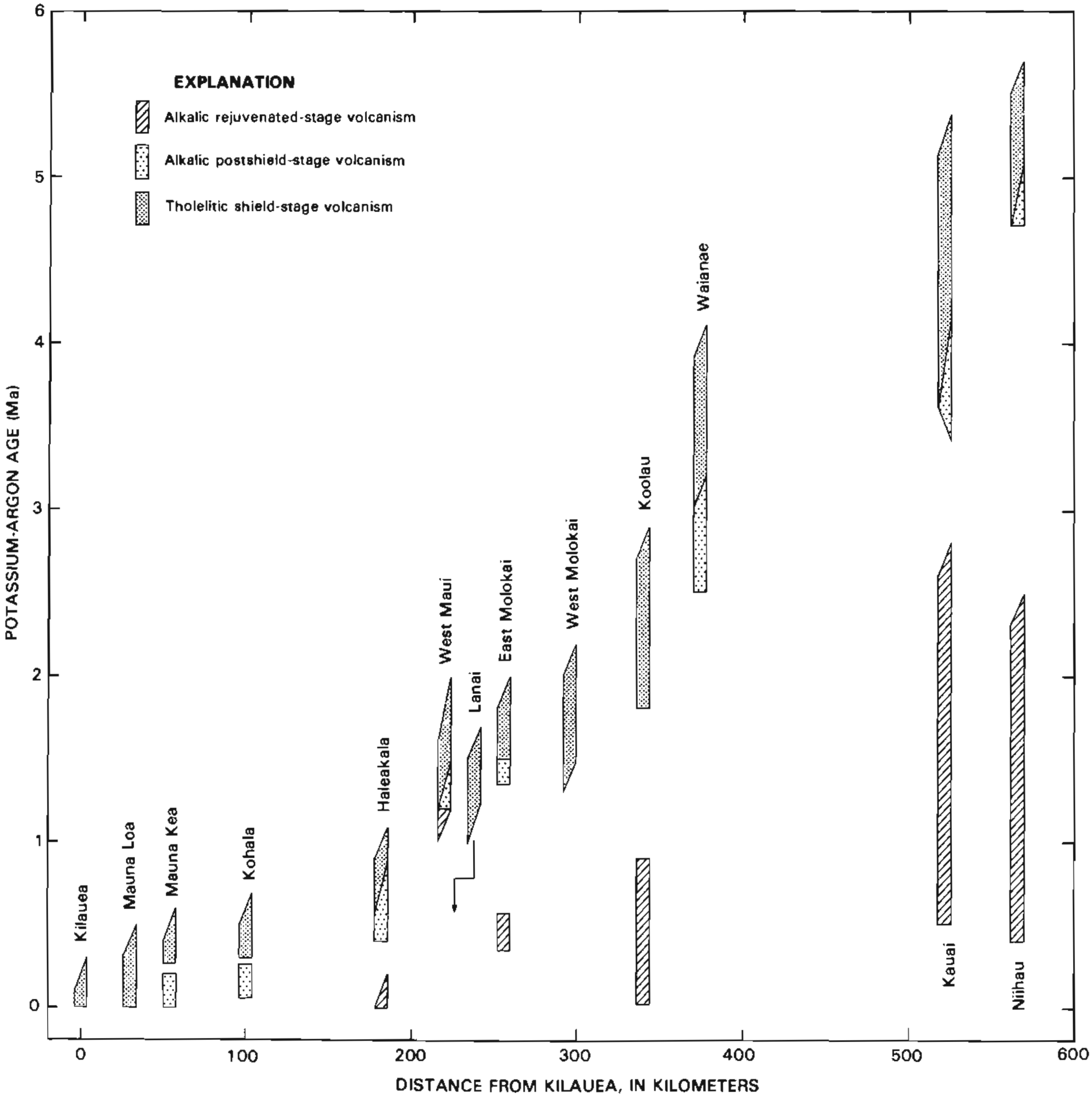

FIGURE 1.6.—Known durations of tholeiitic shield, alkalic postshield, and alkalic rejuvenated-stage volcanism for dated volcanoes of principal Hawaiian Islands. Angled lines indicate overlapping or uncertain ages or overlapping volcanism. Data from sources discussed in appendix 1.1. Data for Niihau and for Kauai (Koloa Volcanics) are from G.B. Dalrymple (unpublished data, 1985).

propagation on a small scale as a working hypothesis. It is unlikely that the cause of this nonlinear propagation, if real, will be known until more is learned about the hot-spot mechanism.

ERUPTION RATES ALONG THE CHAIN

The bathymetry of the chain as a whole is not well known, particularly for the western Hawaiian Ridge, and the 1970 charts for the North Pacific (Chase and others, 1970) and their 1973 derivative (Chase and others, 1973) are probably still the best published sources available. An updated bathymetric chart for the Emperor Seamounts (Clague and others, 1980) was based on the data used by Chase and others (1970) and additional geophysical profiles collected between 1970 and 1979; recently published bathymetry for much of the central part of the Emperor Seamounts (Smoot, 1982) is based on previously classified Navy multibeam data. The gross structure of the Emperor Seamounts is little changed in the later charts, but the shapes and locations of some individual volcanoes changed dramatically (fig. 1.7).

Bargar and Jackson (1974) compiled volume data along the chain and identified individual volcanic centers and their rift systems using the bathymetry of Chase and others (1970). From the more accurate multibeam data it is clear that many of the volcanic centers and rift zones identified by Bargar and Jackson are incorrect in detail. Because the number and general sizes of the volcanoes change little on the later charts, we have used Bargar and Jackson's volume estimates rather than engage in the laborious process of calculating new ones from the newer data. We suspect that the volumes based on multibeam data would vary relatively little from those of Bargar and Jackson.

The cumulative volume of the volcanoes is plotted in figure 1.8 against distance from Kilauea beginning at Tenchi Seamount, 500 km north of Suiko. It is clear that the volume of eruptive products per unit distance along the chain has not been constant over the past 70 million years.

We have calculated dV/dx, where V is volume and x is distance, for segments of the chain, which are summarized in table 1.6. Also listed are dx/dt, where t is time, calculated from the age relations along the chain, and the derived quantity dV/dt for segments along the chain. These calculations clearly show that the volumes erupted per unit distance along the chain and per unit time increase from the Emperor Seamounts to the Hawaiian Ridge and to the Hawaiian Islands. The present-day eruption rate for Kilauea alone, when compared to eruption rates along the Hawaiian Ridge and Emperor Seamounts, demonstrates that the Hawaiian hot spot is presently producing large volumes of lava at the greatest eruption rates in its known history. The average eruption rate from Hualalai to Kilauea is 5 times that for the islands as a whole and nearly 22 times the rate for the entire chain. The only section of the chain where volumes do not increase toward the present is the westernmost section of the Hawaiian Ridge, which formed immediately following the change in plate motion recorded as the Hawaiian-Emperor bend. This change in plate motion was followed by a virtual cessation of volcanic activity that lasted for nearly 10 m.y.

PETROLOGY OF THE HAWAIIAN-EMPEROR VOLCANIC CHAIN

EARLY WORK: LAVA SERIES AND DIFFERENTIATES

Early observers of Hawaiian eruptions rather uniformly agreed that the lava originated "in the bowels of the earth." As time progressed this view was expanded upon, but it was not until the 1950's and 1960's that the lava source and the processes generating the various lava types were discussed in detail. S. Powers (1920) proposed that nepheline basalt and trachyte were formed by differentiation of basaltic magma because of their occurrence late in the eruptive sequence. He wrote (S. Powers, 1920, p. 280): "Each volcano has arisen at an intersection in a fracture system in the earth's crust, has been fed from the same primal source, and has finally lost connection with that source. When this takes place differentiation may proceed in the magma chambers of large volcanoes and the extreme products of Hawaiian volcanism, nepheline basalt and trachyte, may appear either at the close of the main volcanism or in a later phase after extensive erosion."

This viewpoint, that there was a single primary Hawaiian magma from which the varieties of lava evolved by means of differentiation, was popular well into the 1960's. H. Powers (1935) expressed a similar view, although he showed that fractional crystallization alone could not explain the differentiation of Hawaiian basalt. Macdonald (1949) proposed that the sole primary Hawaiian lava was olivine basalt, although his calculated average included both alkalic and tholeiitic olivine basalt analyses (which he did not distinguish at that time). He also proposed that andesine andesite (hawaiite), oligoclase andesite (mugearite), and trachyte were successive differentiates from an olivine basalt parental lava. This view is now known to be incorrect because Macdonald's calculated olivine basalt was basically a tholeiitic basalt in composition. He further inferred that picritic basalt of the oceanite type (here termed picritic tholeiitic basalt) formed by the accumulation of olivine and that ankaramite was not an oceanite that simply accumulated clinopyroxene. This last idea is correct, ankaramite being alkalic in composition whereas picritic basalt of the oceanite type is tholeiitic. In order to differentiate ankaramite and nepheline basalt from the parental olivine basalt, Macdonald (1949) proposed that limestone assimilation and selective remelting (wall-rock assimilation) were important processes. He correctly inferred that the dunite xenoliths so common in alkalic lava from the postshield and rejuvenated stages formed by accumulation of olivine followed by recrystallization.

Tilley (1950) recognized that the bulk of the primitive shields was made of tholeiitic basalt and that alkalic rocks erupted only during the declining stages of activity. He proposed that alkalic olivine basalt was derived from tholeiitic basalt by crystal fractionation. H. Powers (1935) had, however, earlier noted that primitive lava was silica saturated, whereas the late differentiated lava was silica undersaturated; he argued that these lavas could therefore not be simply related to one another by crystal fractionation.

New concepts important to understanding the origin of Hawaiian lava were introduced by H. Powers (1955). He clearly established that the abundant rocks termed olivine basalt in the shields are silica saturated and noted that they are compositionally distinct for individual volcanoes. He proposed the concept of magma batches to account for the subtle differences between the lava of different shields. He also reiterated that olivine basalt erupted during the declining stages of activity is silica undersaturated. His discussion of fractionation trends for tholeiitic and alkalic basalt is nearly identical to present-day views. He further recognized that earthquakes associated with volcanic activity gave a minimum depth of magma generation which he took to be 48–56 km (30–35 miles). His estimates of the source rocks that could be melted to produce basalt and of the causes of melting provided a framework for experimental research for many years. In particular, he noted that basalt could be generated at depth by wholesale melting of rocks of basaltic composition or by partial melting of peridotite. The models of melting he considered all assumed that it was caused by an increase in temperature. He dismissed exothermic nuclear processes

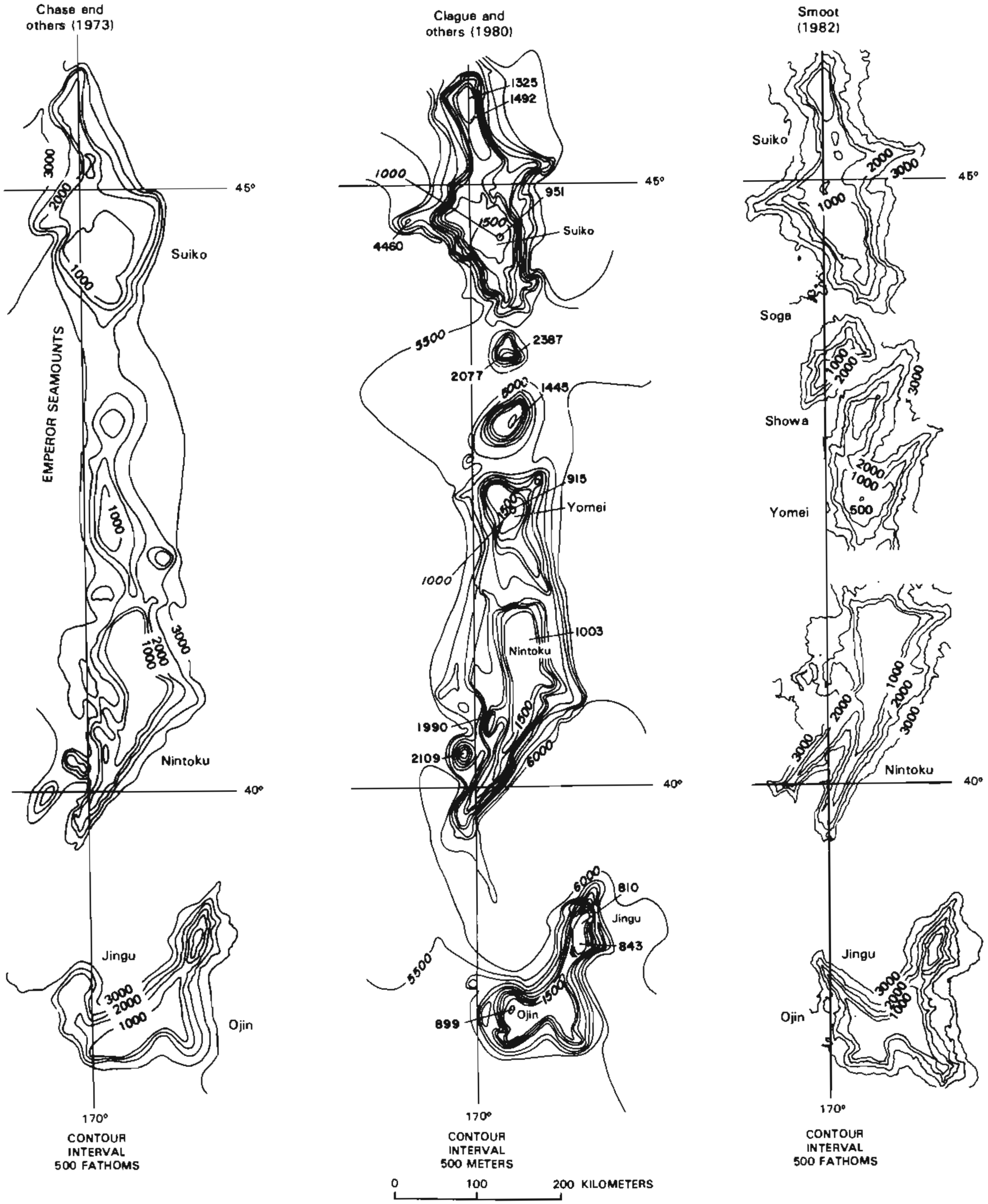

FIGURE 1.7.—Comparison of bathymetry of central Emperor Seamounts from Chase and others (1973; left), Clague and others (1980b; center) and Smoot (1982; right). General size and shape of seamounts were fairly well mapped by bathymetric sounding (left and center), but multibeam bathymetry (right) adds wealth of detail. Contour intervals are 500 fathoms for left and right figures and 500 m for center figure.

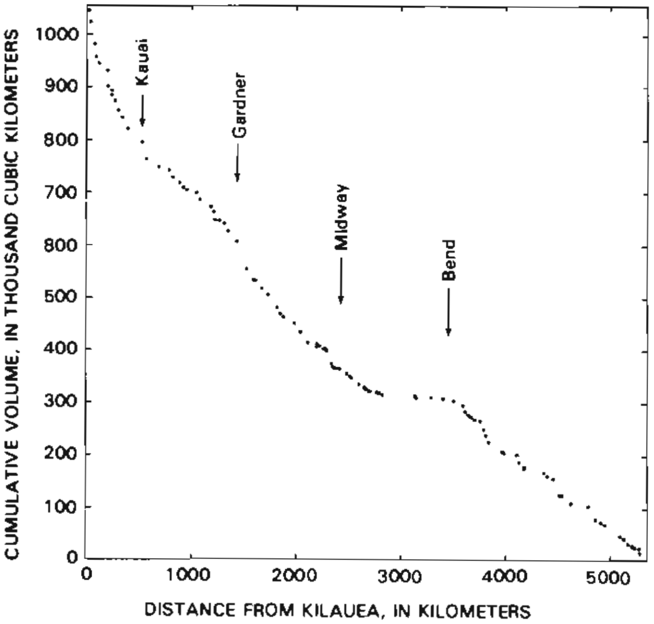

FIGURE 1.8.—Cumulative volcanic volume along Hawaiian-Emperor Chain plotted as a function of distance from Kilauea (along trend of chain). Average volume increment rate (dV/dx) for Emperor Chain is 0.16×10^3 km^3/km. Just east (left) of the bend there is a segment of very low volcanic productivity, in which only 0.02×10^3 km^3/km was erupted. Remainder of submarine portion of the Hawaiian Chain has an average dV/dx of 0.20×10^3 km^3/km. In Hawaiian Islands section from Kauai to Haleakala can be fit by 0.40×10^3 km^3/km and that from Haleakala to Kilauea by 1.1×10^3 km^3/km.

in the crust because Hawaiian lava is not enriched in U, Th, or K. He emphasized convection from hotter regions deep in the mantle and friction produced by dynamic processes (he proposed tides). His convection model is very similar to later plume models and his friction model to at least a part of later thermal-feedback models, both of which are discussed more thoroughly later in this paper.

Kuno and others (1957) clearly demonstrated that closed-system crystal fractionation of tholeiitic basalt led to generation of granophyre in the differentiation of thick lava bodies. They related picritic tholeiitic basalt, olivine tholeiitic basalt, tholeiitic basalt, and granophyre as one differentiation sequence and alkali olivine basalt, picrite basalt of ankaramite type (here called ankaramite), hawaiite, mugearite, and trachyte as another differentiation sequence. They presented trace-element data, which they used to evaluate the proposed fractionation trends. Most importantly, they dismissed any fractionation relation between tholeiitic and alkalic basalt and proposed that they originated independently "through melting of the earth's material under different sets of physical conditions" (Kuno and others, 1957, p. 214). They argued that both lava types were generated by partial melting of peridotite, but that alkalic basalt was derived at greater depth. Their discussion implies that the source rocks were homogeneous and that only the physical conditions of melting varied. In addition, the alkali-silica diagram, widely used to distinguish between tholeiitic and alkalic lava, was first presented in this paper.

Eaton and Murata (1960) published a detailed study locating earthquake epicenters as deep as 60 km beneath Kilauea using basically the same data cited by Powers (1955). These observations establish a minimum depth of magma generation for tholeiitic shield lava of greater than 60 km, although they still allow for selective melting (wall-rock reaction) at shallower depths (Macdonald, 1968).

Macdonald and Katsura (1962, 1964) established the tholeiitic character of the early lava on Kohala and West Maui, where the known late-stage lava is alkalic. They also demonstrated that the subtle variations in composition of the tholeiitic basalt from different volcanoes were unrelated to the type of alkalic cap that followed (Kohala or Haleakala type). In contrast to the interpretations of Tilley (1950), H. Powers (1955), and Kuno and others (1957), Macdonald and Katsura (1964) proposed that alkalic basalt formed by differentiation of tholeiitic basalt. They cited as evidence the interbedded sequence of tholeiitic and alkalic flows, including some of transitional composition, that occur in Haleakala-

TABLE 1.6.—*Eruptive rates along the Hawaiian-Emperor Chain*

[Volume/distance data from figure 1.8; propagation rate data from table 1.5, except for Kilauea to Hualalai; recent data for Kilauea from Dzurisin and others (1984), based on combined eruption-intrusion rate]

Segment	Volume/distance, dV/dx (10^3 km^3/km)	Propagation rate, dx/dt (km/m.y.)	Eruption rate dV/dt (10^3 km^3/m.y.)
Kilaues (1956-1983)	---	---	86
Kilauea to Hualalai	1,500	250	290
Hualalai to Waianae	400	101	40
Hawaiian Islands (0-5.5 Ma)	---	---	56
Waianae to Gardner Pinnacles	190	101	19
Gardner Pinnacles to volcano 57	200	68	14
Volcano 57 to Hawaiian-Emperor bend	20	68	1
Emperor Seamounts	160	72	12
Average for entire chain	---	---	13

type volcanoes between the tholeiitic shield lava and the later alkalic postshield-stage lava and proposed that volatile transfer might be an important differentiation process. They discussed thoroughly the fractionation sequences of both alkalic and tholeiitic lava and related the Mauna Kuwale rhyodacite to tholeiitic lava of the Waianae Range.

The years 1964–68 produced new insights from a variety of studies. The first isotopic data from Hawaiian lava (Lessing and Catanzaro, 1964; Hamilton, 1965; Powell and DeLong, 1966; Tatsumoto, 1966) clearly demonstrated that the source rocks for Hawaiian lava were heterogeneous. Experimental studies at high pressure and temperature (for example, O'Hara, 1965; Green and Ringwood, 1967) added new data bearing on the mineralogy of potential source rocks and the physical conditions of melting. At the same time, trace-element data began to be used to evaluate Hawaiian petrogenetic processes (Schilling and Winchester, 1966; Gast, 1968). Studies of Hawaiian xenoliths (White, 1966) added to the abundant new data being used to evaluate the petrogenesis of Hawaiian lava and the nature of the source rocks. This period marks a transition from relatively qualitative models of petrogenesis to modern quantitive modeling and testing of basalt petrogenesis. To a great degree present day petrogenic models are based on these same types of data and similar quantitative modeling techniques. However, because modern isotopic and trace-element data are more accurate and precise, the models proposed are more refined and complex.

Macdonald (1968) followed Green and Ringwood (1967) and proposed that the tholeiitic, alkalic, and nephelinitic lava types were derived from a single parent magma of olivine tholeiitic basalt composition. He proposed that the compositional variations reflect the depth at which fractional crystallization occurred with tholeiitic basalt fractionated at shallow depths, alkalic basalt at moderate depths, and nephelinitic lava at depths of several tens of kilometers. He further argued that the primary magma is olivine tholeiitic basalt rather than tholeiitic basalt because most lava has lost olivine, which accumulated within the magma chambers to form the high-density masses discovered by gravity surveys (summary and references in Jackson and others, 1972). Macdonald (1968) noted that the highest temperature lava from the Kilauea Iki eruption contained 27–30 percent olivine and proposed that this closely approximated primary magma. Wright (1973) calculated the bulk composition of the same eruption and proposed it as a representative parental (but not necessarily primary) composition for Kilauea tholeiitic basalt. Macdonald (1968) presented quantitative models showing that ankaramite is alkalic basalt plus olivine and clinopyroxene and that hawaiite is alkalic basalt minus olivine, clinopyroxene, plagioclase, and magnetite. This type of mass-balance approach was later refined by Wright (1971) and Wright and Fiske (1971) to demonstrate the roles of fractionation and hybridization in generating basalt at Kilauea and Mauna Loa. The debate about whether primary tholeiitic magma is olivine rich or olivine poor continues today (see Wright and Helz, chapter 23; Wright, 1984; Budahn and Schmitt, 1984). Extreme compositions are liquids with 20 percent MgO (Wright, 1984) and average tholeiitic basalt with 9 percent MgO (Powers, 1955).

Macdonald (1968) also calculated average compositions of Hawaiian lava from the different eruptive stages. His average compositions, recalculated on a dry-reduced normalized basis, are presented in table 1.7. These averages clearly show that lava of the tholeiitic shield stage is silica saturated and that of alkalic postshield and rejuvenated stages is silica undersaturated. The presence of normative hypersthene in the mugearite, benmoreite, and trachyte, which are derived from undersaturated alkalic basalt, reflects fractionation of Fe-Ti oxides, which enriches the residual melt in silica. Rejuvenated-stage alkalic basalt contains greater than 5 percent normative nepheline, and average nephelinite and nepheline melilitite contain normative leucite. Alkalic basalt of the preshield and rejuvenated stages are similar in composition. The preshield Loihi Seamount averages are calculated from Moore and others (1982), Frey and Clague (1983), and D.A. Clague (unpub. data, 1985).

XENOLITH DISTRIBUTIONS

In a detailed analysis of the xenolith populations in Hawaiian lava, Jackson (1968) subdivided the xenoliths into dikes and sills, cumulates, and metamorphic rocks. His breakdown of the relative abundances and types of xenoliths is given in table 1.8, modified to include xenoliths found in Loihi Seamount alkalic preshield lava. Jackson noted that only those xenoliths with metamorphic textures could represent either mantle source rocks or mantle residua left after partial melting. The dikes, sills, and some, but not all, of the cumulate rocks are cognate or from shallow depths. The cumulate xenoliths from Hualalai Volcano appear to come from a variety of sources, including cumulates formed as part of oceanic crustal layer 3, cumulates of tholeiitic Hawaiian shield lava, and cumulates of lava from the alkalic postshield stage (D.A. Clague, unpub. data, 1985). The single cumulate xenolith from Loihi Seamount presumably represents a cumulate of ocean crustal layer 3.

Jackson and Wright (1971) proposed that the abundant dunite xenoliths in the Honolulu Volcanics represent residue left after melting the mantle to form Koolau shield tholeiite, an interpretation with which we disagree. Jackson and Wright (1971) inferred that the garnet lherzolite and lherzolite found only in alkalic lava from the rejuvenated stage were potential mantle source rocks. The difference in xenolith populations for the three alkalic eruptive stages is striking since only the lava from the preshield stage and rejuvenated stage contain xenoliths that formed at depths greater than about 20 km. Although it would be useful if these xenolith populations reflected the mantle through which the lava ascends, it seems more likely that they reflect the development of shallow magma storage reservoirs, which act as hydraulic filters and remove xenoliths carried up from greater depths in much the same way as lakes remove sediment from rivers.

Lava stored in a shallow magma reservoir, either within a few kilometers of the surface or at the base of the oceanic crust, lose any xenoliths they may have acquired during ascent and from this point can only entrain xenoliths that occur at shallower levels in the volcanic system. However, lava of the preshield and rejuvenated stages erupts in small volumes at infrequent intervals and probably no shallow magma storage reservoirs exist. During the shield stage, tholeiitic lava erupts in large volumes at frequent intervals from a

TABLE 1.7.—*Average compositions and norms of major Hawaiian lava types*

[All figures in weight percent; -- not present. Normative components calculated with original FeO/Fe_2O_3 ratios. See Macdonald (1968) for remainder of norms for all but the alkalic preshield stage. Data for alkalic preshield stage from Frey and Clague (1983) and D.A. Clague (unpub. data, 1985)]

Stage	Alkalic preshield				Tholeiitic shield		Alkalic postshield						Alkalic rejuvenated			
Lava type	Tholeiite and olivine tholeiitic basalt	Transitional basalt	Alkalic basalt	Basanite	Picritic tholeiitic basalt	Tholeiitic and olivine tholeiitic basalt	Ankaramite	Alkalic basalt	Hawaiite	Mugearite	Benmoreite	Trachyte	Alkalic basalt	Basanite	Nephelinite	Melilitite
Chemical composition																
SiO_2	48.4	48.3	45.6	43.5	46.7	50.0	44.6	45.9	48.6	52.1	58.3	62.8	45.2	44.6	40.6	37.8
Al_2O_3	12.2	13.6	11.6	11.1	8.5	14.1	12.2	14.9	16.1	17.1	18.0	18.3	12.8	12.8	11.6	11.2
FeO*	12.0	12.3	12.4	13.6	12.1	11.3	12.6	13.0	12.2	10.0	7.5	4.5	12.4	12.5	13.3	14.6
MgO	11.2	7.5	13.5	12.2	20.9	8.5	13.1	7.9	4.9	3.3	1.6	.4	11.5	11.3	12.4	13.0
CaO	11.0	11.4	10.4	11.4	7.4	10.4	11.6	10.6	8.1	6.2	3.6	1.2	11.5	10.7	13.1	14.1
Na_2O	2.1	2.7	2.5	3.2	1.6	2.2	1.9	3.0	4.3	5.5	6.0	7.5	2.7	3.6	3.9	4.2
K_2O	.4	.7	.8	1.3	.3	.4	.7	1.0	1.5	2.1	2.9	4.3	.9	1.0	1.2	1.0
TiO_2	2.3	3.1	2.7	3.1	2.0	2.5	2.7	3.0	3.4	2.4	1.2	.5	2.3	2.6	2.9	2.9
P_2O_5	.2	.3	.3	.5	.2	.3	.3	.4	.7	1.1	.7	.2	.5	.5	.9	1.1
MnO	.2	.2	.2	.2	.2	.2	.2	.2	.2	0.2	.2	.2	.2	.2	.2	.1
Normative composition																
Q	--	--	--	--	--	2.2	--	--	--	--	--	--	--	--	--	--
Ne	--	--	2.7	11.8	--	--	2.6	2.6	0.3	--	--	--	6.0	10.5	17.3	18.7
Lc	--	--	--	--	--	--	--	--	--	--	--	--	--	--	5.7	4.8
Hy	14.3	6.3	--	--	15.9	21.5	--	--	--	2.7	4.0	.4	--	--	--	--
Ol	10.5	5.9	23.1	17.7	29.5	--	22.2	13.2	6.7	2.1	--	--	19.3	17.9	14.9	20.2

shallow magma storage reservoir and perhaps a deeper staging zone (see review by Decker, chapter 42). During the alkalic postshield stage, lava erupts in small volumes at infrequent intervals, though in larger volumes and at more frequent intervals than during the alkalic preshield or rejuvenated stages. During this stage, lava apparently resides in reservoirs below the base of the oceanic crust (Clague and others, 1981) for time periods sufficient for the dense peridotite xenoliths to settle out. Tholeiitic lava at Kilauea passes through two such filters, one an intermediate-depth (20–30 km) staging area, the second a well-defined and complex shallow reservoir system 3–7 km beneath the surface. After passing through these filters, the lava can only incorporate as xenoliths the wall rocks occurring at depths shallower than the shallowest reservoir (dikes, sills, and olivine cumulates). Alkalic lava of the postshield stage contains abundant xenoliths of dunite, which have CO_2 inclusions that were trapped at depths of at least 15 km, and cumulate xenoliths of rocks from oceanic crustal layer 3 (Roedder, 1965; D.A. Clague, unpub. data, 1985). These observations suggest that in the postshield stage any shallow magma chamber of the shield stage no longer exists but an intermediate staging area at 20–30 km, similar to that beneath Kilauea, acts as an effective filter that removes any lherzolite or garnet peridotite xenoliths. Lava may fractionate in this zone and, upon movement to the surface, entrain xenoliths of ocean crust rocks and cumulates formed in earlier volcanic stages at shallow depth. The presence of xenoliths that originate at great depth in alkalic lava of both the preshield and rejuvenated stages implies that neither shallow nor intermediate staging area acts as an effective filter in these stages. The near-primary character of the host lava also indicates that the lava was not stored at shallow depths but rather moved from its source region to the surface in short time periods (Clague and Frey, 1982).

This analysis leads us back to Jackson's (1968) conclusion that only the xenoliths with metamorphic textures could possibly be mantle source rocks or residua. We conclude that only the lherzolite and garnet peridotite xenoliths represent mantle rocks from below the magma storage zone that appears to have existed beneath Hawaiian shield volcanoes at depths of 20–30 km. The dunite and wehrlite xenoliths are either deformed cumulates formed during

TABLE 1.8.—*Distribution of Hawaiian xenolith types*

[Data from Jackson (1968) except the alkalic preshield stage which is from D.A. Clague (unpub. data, 1985)]

		Xenolith type (percent)		
Eruptive stage	Lava type	Dike rocks and vein fillings	Cumulates	Metamorphic rocks
Alkalic rejuvenated	alkalic basalt basanite nephelinite nepheline melilitite	(<1)	(1) olivine cumulates dominant	(99) dunite ≅ wehrlite ≅ lherzolite> harzburgite, garnet peridotite locally
Alkalic postshield	alkalic basalt	(3) veins dominant	(35) olivine cumulates> pyroxene cumulates	(62) dunite>> wehrlite
	ankaramite	(14) dikes and sills dominant	(53) pyroxene cumulates> olivine cumulates	(33) dunite>> wehrlite
	hawaiite mugeartie trachyte	(14) dikes and sills dominant	(57) pyroxene cumulates> olivine cumulates	(29) dunite>> wehrlite
Tholeiitic shield	tholeiitic basalt	(75) dikes and sills dominant	(25) olivine cumulstes dominant	none
Alkalic preshield (Loihi)	alkalic basalt basanite	none	(1) olivine cumulates	(99) dunite>> lherzolite

earlier stages in the volcano's growth or cumulates formed during formation of oceanic crust (see Sen, 1983, 1985; Kurz and others, 1983; Sen and Presnall, 1985).

The remaining xenoliths of spinel lherzolite, rare harzburgite, and rare garnet peridotite that occur in alkalic lava of the rejuvenated stage and even more rarely in alkalic lava of the preshield stage therefore are the only xenoliths of deeper mantle material. Spinel lherzolite xenoliths have many characteristics that imply a close genetic relationship to midocean-ridge basalt; however, both the Sr-isotopic and rare-earth data indicate that these xenoliths have been enriched by mixing between residua left after formation of midocean-ridge basalt and an enriched magma or vapor (Frey 1980, 1984; Wright, 1984; Frey and Roden, in press). These xenoliths probably represent depleted oceanic lithosphere modified by processes related to Hawaiian magmatism.

The final group of xenoliths consists of pyroxenite, websterite, and garnet-bearing pyroxenite and websterite. These occur in only a few vents of the alkalic rejuvenated stage in the Honolulu Volcanics (Jackson and Wright, 1970) and on Ka'ula Island (Garcia, Frey, and Grooms, in press). These rocks occur both as separate xenoliths and as layers in xenoliths. Some of these xenoliths have been called garnet lherzolite (Jackson and Wright, 1970), but they are not merely a higher pressure assemblage of spinel lherzolite because their bulk compositions are distinct (Jackson and Wright, 1970; Sen, 1983). The iron-rich olivine in all the xenoliths of this group led Sen (1983) to argue that they represent neither source rocks nor residua related to Hawaiian lava. Frey (1980, 1984) has argued that they may represent crystal accumulates from alkaline Hawaiian magma. We conclude that none of the xenoliths found in Hawaiian lava represent mantle source rocks or residua related to Hawaiian volcanism. They do, however, provide insight into the conduit systems through which much of this lava passed.

Jackson and Wright (1970) demonstrated that xenoliths in the Honolulu Volcanics were compositionally zoned in a geographic sense with respect to the Koolau caldera; abundant dunite near the caldera grades into lherzolite and finally garnet-bearing websterite and pyroxenite away from the caldera. Jackson and Wright (1970) combined these observations with experimental petrologic and geophysical data to construct a cross section through the mantle and crust beneath Oahu (fig. 1.9). Their cross section emphasizes the mineralogic and compositional heterogeneity of the mantle beneath Hawaiian volcanoes. However, the origins of many of the rock types are now thought to be different from those proposed by Jackson and Wright (1970). A more recent model by Sen (1983) shows plagioclase lherzolite beneath the oceanic crust to a depth of about 30 km (defined by the limit of plagioclase stability), spinel lherzolite from 30 to nearly 50 km, and garnet lherzolite below about 50 km. The zone beneath the volcanoes includes cumulate dunite to depths

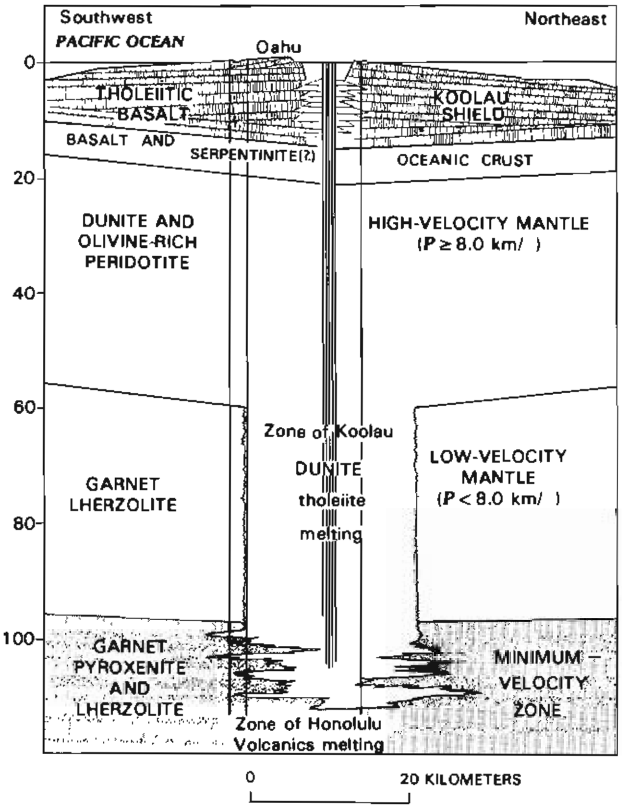

FIGURE 1.9.—Cross section beneath Oahu from Jackson and Wright (1970). Dunite zone inferred to be mantle residue left behind from partial melting that forms Koolau tholeiitic shield lava. Configuration of rock types and their mode of origin are far different from those shown in figure 1.10.

of about 15 km (fig. 1.10). The areal distribution of xenoliths observed by Jackson and Wright (1970) reflects passage of the Honolulu Volcanics lava through the zone of dunite cumulates.

PETROLOGY OF LAVAS ALONG THE VOLCANIC CHAIN

In the middle to late 1970's new studies added data to the already complex data array on Hawaiian volcanoes. Studies on lava recovered from the older submarine portions of the chain (Clague, 1974; Dalrymple and others, 1974, 1977, 1981; Clague and others, 1975; Dalrymple and Clague, 1976; Kirkpatrick and others, 1980; Clague and Frey, 1980; Lanphere and others, 1980; Dalrymple and Garcia, 1980; Garcia, Grooms, and Naughton, in press) clearly demonstrate that the volcanoes of the entire Hawaiian-Emperor volcanic chain erupted tholeiitic basalt and picritic tholeiitic basalt similar to those of the shield stage in the Hawaiian Islands. In addition, alkalic lava similar to that erupted during the postshield stage in the Hawaiian Islands, including hawaiite, mugearite and trachyte, is commonly recovered from the older volcanoes. In the drill holes on Ojin and Suiko, tholeiitic lava occurs below alkalic lava, as in the Hawaiian Islands. Some samples are chemically and mineralogically similar to alkalic rejuvenated-stage lava from the Hawaiian Islands (table 1.2). The identification of which dredged or drilled lava samples erupted during which eruptive stage relies on comparison of the major-element compositions to those of the various Hawaiian lava types (table 1.7) in conjunction with trace-element ratios (Clague and Beeson, 1980; Clague and others, 1980c; Frey and Clague, 1983) and mineral compositions (Keil and others, 1972; Fodor and others, 1975; Clague and others, 1980a). In particular, we have found that the composition of groundmass pyroxene and the K/Ba and P_2O_5/Zr ratios seem to separate alkalic basalt of the postshield and rejuvenated stages. Rejuvenated-stage alkalic basalt has lower K/Ba and higher P_2O_5/Zr ratios and pyroxene with more calcic compositions and higher concentrations of Na, Ti, and Al than postshield-stage alkalic basalt. Lava samples recovered from the volcanoes west of the principal Hawaiian Islands are discussed in appendix 1.1 and summarized in table 1.9.

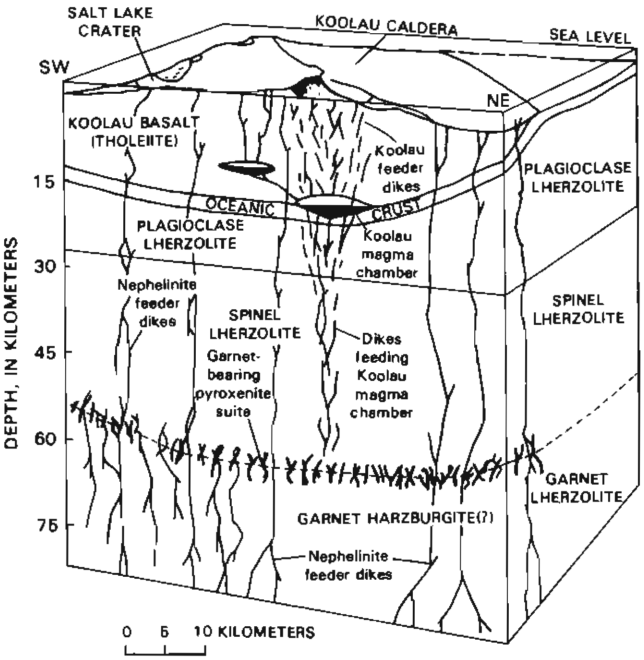

FIGURE 1.10.—Cross section beneath Oahu from Sen (1983) showing configuration of various mantle source and residual rocks brought to surface as xenoliths of abundant dunite, lherzolite, and garnet peridotite by rejuvenated-stage Honolulu Volcanics.

Several conclusions may be drawn from these studies of samples from along the Hawaiian-Emperor Chain. The first conclusion is that the Hawaiian hot spot has produced very similar lava types in the same eruptive sequence for at least the last 65 m.y. (table 1.10). Samples from the same eruptive stage are similar to one another in both major- and trace-element compositions, including rare-earth elements (Clague and Frey, 1980; Frey and Roden, in press). Isotopic studies indicate, however, that small systematic changes occur over time (Lanphere and others, 1980; Unruh and

TABLE 1.9.—*Rock types and inferred volcanic stages represented along the Hawaiian-Emperor Chain*

[X, present; --, not present or not known; (T), transitional; volcano numbers from Bargar and Jackson (1974)]

Volcano		Shield stage			Alkalic postshield stage						Alkalic rejuvenated stage				
Number	Name	Tholeiitic basalt	Picritic tholeiitic basalt	Rhyodacite	Alkalic basalt	Ankaramite	Hawaiite	Mugearite	Trachyte	Phonolite	Alkalic basalt	Basanite	Nephelinite	Melilitite	Tephrite
1	Kilauea	X	X	--	--	--	--	--	--	--	--	--	--	--	--
2	Mauna Loa	X	X	--	--	--	--	--	--	--	--	--	--	--	--
4	Hualalai	X	X	--	X	X	--	--	X	--	--	--	--	--	--
3	Mauna Kea	X	X	--	X	X	X	--	--	--	--	--	--	--	--
5	Kohala	X	--	--	--	--	--	X	X	--	--	--	--	--	--
6	Haleakala	X	--	--	X	X	X	X	--	--	X	X	--	--	--
7	Kahoolowe	X	X	--	--	X	--	--	--	--	X?	--	--	--	--
8	West Maui	X	X	--	X	X	--	X	X	--	--	X	--	--	--
10	East Molokai	X	X	--	X	X	X	X	X	--	X	X	--	--	--
9	Lanai	X	X	--	--	--	--	--	--	--	--	--	--	--	--
11	West Molokai	X	X	--	X	--	X	--	--	--	--	--	--	--	--
12	Koolau	X	X	--	--	--	--	--	--	--	X	X	X	X	--
13	Waianae	X	X	X	--	--	X	--	--	--	--	--	--	--	--
14	Kauai	X	X	--	--	--	X	--	--	--	X	X	X	X	--
15	Niihau	X	X	--	X	--	--	--	--	--	X	--	--	--	--
15A	Kaula	X	--	--	--	--	--	--	--	X	--	X	--	--	--
17	Nihoa	X	X	--	--	--	--	--	--	--	--	--	--	--	--
19	Unnamed Seamount	--	X	--	--	--	--	--	--	--	--	--	--	--	--
20	Unnamed Seamount	X	--	--	--	--	--	--	--	--	--	X	--	--	--
21	Unnamed Seamount	--	X	--	--	--	--	--	--	--	--	--	--	--	--
23	Necker	--	X	X?	--	--	X	--	--	--	--	--	--	--	X?
26	La Perouse Pinnacles	--	X	--	--	--	--	--	--	--	--	--	--	--	--
30	Gardner Pinnacles	--	X	--	X	--	--	--	--	--	--	--	--	--	--
38	Brooks Bank	X	--	--	--	--	X	--	--	--	--	--	--	--	--
29	St. Rogatein Bank	--	--	--	--	--	X	--	--	--	--	--	--	--	--
36	Laysan	--	--	--	--	--	X	X	--	--	--	--	--	--	--
37	Northampton Bank	X	X	--	--	--	--	--	--	--	--	--	--	--	--
39	Pioneer Bank	X	--	--	--	--	--	--	--	--	--	--	--	--	--
50	Pearl and Hermes Reef	--	--	--	X	--	X	--	--	X	--	--	--	--	--
51	Ladd Bank	--	--	--	--	--	--	--	--	--	--	--	X	--	--
52	Midway Island	X	--	--	--	--	X	X	--	--	--	--	--	--	--
53	Nero Bank	--	X	--	--	--	--	--	--	--	--	--	--	--	--
57	Unnamed Seamount	--	--	--	X	--	--	--	--	--	--	--	--	--	--
63	Unnamed Seamount	--	--	--	--	--	--	--	--	--	--	--	--	--	[1]X
65	Colahan Seamount	(T)	--	--	--	--	--	--	--	--	--	--	--	--	[1]X
65A	Abbott Seamount	(T)	--	--	--	--	--	--	--	--	--	--	--	--	--
67	Daikakiyi Seamount	X	--	--	X	--	--	--	--	--	--	--	--	--	--
69	Yuryaku Seamount	--	--	--	X	--	--	--	--	--	--	--	--	--	--
72	Kimmei Seamount	--	--	--	X	--	--	--	--	--	--	--	--	--	--
74	Koko Seamount (southeast)	X	--	--	X	--	X	X	X	X	--	--	--	--	--
76	Koko Seamount (northwest)	X	--	--	--	--	--	--	--	--	--	--	--	--	--
81	Ojin Seamount	X	--	--	--	--	X	--	--	--	--	--	--	--	--
89	Jingu Seamount	--	--	--	--	--	X	X	--	--	--	--	--	--	--
86	Nintoku Seamount	--	--	--	X	--	--	--	--	--	--	--	--	--	--
90	Suiko Seamount (southern)	--	--	--	--	--	--	X?	--	--	--	--	--	--	--
91	Suiko Seamount (central)	X	X	--	X	--	--	--	--	--	--	--	--	--	--
108	Meiji Seamount	X	--	--	--	--	--	--	--	--	--	--	--	--	--

[1] Dredges from unnamed seamount (63) and Colahan Seamount recovered ankaramite, tephrite, and amphibole-bearing hawaiite that are probably rejuvenated stage lava.

TABLE 1.10.—*Composition of tholeiitic basalt from volcanoes of the Hawaiian-Emperor Chain*

[All figures in weight percent, dry reduced normalized average analyses; olivine added or subtracted so that Mg/(Mg+0.85 Fe)=0.70; —, not analyzed; P_2O_5 value in parentheses is high due to marine phosphatization]

Volcano	Kilauea	Mauna Loa	Mauna Kea	Hualalai	Kohala	East Maui	West Maui	Lanai	East Molokai	West Molokai	Koolau	Waianae	
												(upper)	(lower)
SiO_2 —	48.9	50.5	46.4	49.4	48.2	49.7	47.3	49.0	46.4	49.2	51.5	46.9	47.9
Al_2O_3 -	12.1	12.2	12.8	11.8	13.5	13.3	12.6	12.8	12.9	11.8	13.2	13.4	14.1
FeO ---	11.4	11.0	12.3	11.9	11.8	10.9	12.2	11.0	12.4	11.9	10.4	11.9	11.2
MgO ---	12.7	12.3	13.6	13.4	13.1	12.1	13.7	12.3	13.8	13.2	11.7	13.2	12.5
CaO ---	9.7	9.2	9.9	9.2	9.4	9.6	9.8	8.8	9.7	8.9	8.3	9.1	9.6
Na_2O —	1.99	1.98	1.82	1.84	1.62	1.76	1.66	2.13	1.89	2.42	2.47	2.07	1.86
K_2O ---	.44	.36	.28	.28	.10	.33	.23	.11	.20	.18	.27	.53	.26
TiO_2 --	2.34	1.85	2.40	1.75	1.93	2.01	2.14	1.66	2.22	2.08	1.68	2.46	2.20
F_2O_5 --	.22	.21	.23	.16	.20	.13	.20	.18	.25	--	.22	.35	.25
MnO ---	.17	.16	.17	.15	.18	.18	.17	.14	.18	.19	.15	.15	.17

Volcano	Kauai	Niihau	Nihoa	Unnamed (20)	Unnamed (21)	Necker Island	La Perouse Pinnacles	Gardner Pinnacles	Northampton Bank	Pioneer	Dsikakiji	Suiko	
												high TiO_2	low TiO_2
SiO_2 --	48.4	48.4	47.4	46.9	47.1	47.15	47.5	47.6	48.7	48.2	49.7	47.6	47.9
Al_2O_3 -	12.5	12.1	11.5	11.2	11.3	11.1	11.7	12.5	11.4	11.2	11.5	12.7	13.0
FeO ---	11.9	12.1	12.4	12.6	12.4	12.8	11.8	11.3	11.7	11.9	11.5	12.3	11.9
MgO ---	13.3	13.6	13.8	14.0	13.8	14.1	13.1	12.6	13.0	13.3	12.9	13.7	13.2
CaO ---	9.2	8.1	9.4	9.6	9.2	9.8	10.7	10.3	10.1	9.8	9.05	8.7	9.3
Na_2O --	1.93	2.28	1.77	2.06	2.25	1.59	1.82	2.06	2.00	2.20	2.08	2.26	2.26
K_2O ---	.30	.49	.26	.24	.64	.38	.39	.16	.32	.67	.43	.28	.14
TiO_2 —	2.06	2.49	2.59	2.97	2.72	2.47	2.44	1.98	2.26	2.36	2.32	2.10	1.86
P_2O_5 --	.23	.31	(.70)	.28	.35	.36	.34	.26	.23	.17	.36	.22	.16
MnO ---	.17	.16	.15	.15	.15	.17	.20	.16	.16	.14	.16	.18	.18

others, 1983). The lower $^{87}Sr/^{86}Sr$ ratios and higher $^{143}Nd/^{144}Nd$ ratios of lava from the central Emperor Seamounts compared to those of lava from the Hawaiian Islands and Ridge imply that tholeiitic lava erupted 65 m.y. ago was derived from a more depleted source than that erupting today. Lanphere and others (1980) correlated this observation with the data shown in figure 1.3 to suggest that the chemistry of Hawaiian tholeiitic lava has varied as a function of the age and thickness of the oceanic lithosphere beneath each volcano when it was constructed. The correlation suggests that the oceanic lithosphere forms at least part of the source material for Hawaiian tholeiitic magma, or that the magma partially reequilibrates with the oceanic lithosphere. Wright (1984) proposes that Hawaiian magma originates from oceanic lithosphere converted to asthenosphere.

STRATIGRAPHIC STUDIES IN THE HAWAIIAN ISLANDS

Studies of stratigraphically controlled samples (Beeson, 1976; Clague and Beeson, 1980; Chen and Frey, 1983; Clague and others, 1983; Feigenson, 1984; Lanphere and Frey, 1985) have shown that major-element, trace-element, and isotopic ratios change systematically as a function of time at some Hawaiian volcanoes. These observations are not universal (Stille and others, 1983; Frey and others, 1984) in as much as Waianae and Mauna Kea erupted isotopically similar lava during the tholeiitic shield and alkalic postshield stages. Chen and Frey (1983) observed systematic stratigraphic trends in $^{87}Sr/^{86}Sr$, Rb/Sr, $^{143}Nd/^{144}Nd$, and Sm/Nd ratios in samples from East Maui Volcano. Their data indicate that the tholeiitic lava had higher $^{87}Sr/^{86}Sr$ and Sm/Nd ratios and lower ^{143}/Nd ^{144}Nd and Rb/Sr ratios than the later alkalic lava from the postshield and rejuvenated stages. They proposed a complex mixing model to explain the apparent paradox of having more radiogenic isotopic ratios combined with more depleted trace-element ratios in the same rocks. Their model proposes two sources, a primitive mantle-plume source and a depleted oceanic-lithosphere source, which can mix before melting or can produce partial melts which then mix. They argue that small amounts of small-percentage melts from the oceanic lithosphere (midocean-ridge source) are mixed with enriched mantle or with melts derived from enriched mantle. This model is similar to earlier selective-melting models qualitatively proposed by Green and Ringwood (1967) and Macdonald (1968). It would also be possible to mix small-percentage melts of enriched mantle with the oceanic-lithosphere source (basically an enrichment model) to create the source rocks for Hawaiian magma (Clague and others, 1983; Chen and Frey, 1985), although the measured and calculated compositions do not match as closely as in the model of Chen and Frey (1983). All these models predict a range of source compositions from which the lava is generated.

Other studies emphasize the bulk composition of the source rocks and the processes and physical conditions of the melting process. For example, Clague and Frey (1982), from a detailed trace-element analysis of the rejuvenated stage Honolulu Volcanics on Oahu, concluded that lava ranging from nepheline melilitite to alkalic basalt was generated by 2–11 percent partial melting of a homogeneous garnet (<10 percent) lherzolite source that was carbon bearing. The source had been recently enriched and had a chondrite-normalized La/Yb ratio of 4.4. During melting, phlogopite, amphibole, and a Ti-rich phase (oxide?) remained in the residua, but apatite was completely melted. This model can be combined with the model of Chen and Frey (1983) to generate the source composition indicated for the Honolulu Volcanics (see Roden and others, 1984). The homogeneous composition of the mantle source for the Honolulu Volcanics implies that the recent enrichment event affects a large volume of depleted mantle from which the lava is then generated by partial melting. This is not the same process espoused in the model preferred by Chen and Frey (1983) in which enriched mantle or partial melts of enriched mantle mix with partial melts of depleted mantle. Note that all these models consider only two mixing end members, whereas the isotopic data clearly indicate that at least three distinct source compositions are required (Tatsumoto, 1978; Staudigel and others, 1984). Feigenson (1984) proposed three-end-member mixing models for Kauai lava but did not identify the trace-element signatures of the source components.

The generation of large volumes of tholeiitic lava has been the focus of recent studies by Wright (1984) and Budahn and Schmitt (1984), who used different approaches and reached dramatically different conclusions. Wright (1984) used mass-balance considerations to calculate the components and abundance of material that must be added to depleted lithosphere to generate Hawaiian tholeiitic basalt by large percentages of partial melting (35–42 percent melting). His models did not attempt to calculate the variations in source composition for tholeiitic basalt from the different volcanoes (Leeman and others, 1977, 1980; Basaltic Volcanism Study Project, 1981). Budahn and Schmitt (1984) used inverse procedures to estimate the variations in source composition required to generate the tholeiitic basalt from a number of Hawaiian volcanoes. Their estimated sources had 74–86 percent olivine plus orthopyroxene, 11–21 percent clinopyroxene, and 3–5 percent garnet. All the calculated sources had slightly enriched light-rare-earth-element contents, and low heavy-rare-earth abundances (0.9 to 1.6 times chondrites). They calculated the partial melting at 2–10 percent for these sources. Budahn and Schmitt (1984) did not address the processes that led to creation of these different source compositions, nor did they consider the volumes of mantle source regions required, or the constraints on the production of partial melts provided by Kilauea's magma supply and eruption processes. Wright's (1984) model follows from consideration of these additional constraints. The large difference between the models of Wright (1984) and Budahn and Schmitt (1984) emphasizes the uncertainties concerning the compositions and processes that create the source rocks and the lava of the Hawaiian Islands.

PETROLOGIC STUDIES OF LOIHI SEAMOUNT

Studies of Loihi Seamount have provided new insight in magma genesis in the Hawaiian Islands. Trace-element and isotopic studies demonstrate that the source rocks beneath a single volcano are heterogeneous and require at least three mantle components (Frey and Clague, 1983; Lanphere, 1983; Staudigel and others, 1984). Perhaps more important is the observation of very high $^3He/^4He$ ratios, which imply a primitive undegassed source of volatiles (Kaneoka, chapter 27; Kurz and others, 1983; Rison and Craig, 1983; Kaneoka and others, 1983). The ratio of $^3He/^4He$ is inversely related to the volume of the volcanoes on the Island of Hawaii (Kaneoka, chapter 27; Kurz and others, 1983), suggesting that at smaller volcanoes lava is generated from sources that are largely primitive and not degassed. Another observation is that Hawaiian volcanoes initially erupt alkalic lava generated from heterogeneous source compositions by rather small percentages of partial melting (Moore and others, 1982; Frey and Clague, 1983). The evolutionary sequence at a Hawaiian volcano is therefore from small-volume, infrequent eruptions of small-percentage melts to large-volume, frequent eruptions of large-percentage melts, and then back to small-volume, infrequent eruptions of small-percentage melts (Wise, 1982).

PETROLOGIC OVERVIEW

In summary, the petrology of lava from along the Hawaiian-Emperor Chain indicates that at least three source materials are involved in the generation of Hawaiian lava; one of these sources is apparently the depleted ocean lithosphere, whereas another is relatively primitive undegassed mantle. The third component is less well defined. Since multiple sources are required, mixing of these sources or of melts generated from these sources must occur. The compositions of lava along the chain apparently are related to the age (thickness) of the underlying oceanic lithosphere; the volcanoes formed on younger and thinner oceanic lithosphere were generated from a source with a larger component of the depleted ocean lithosphere. Detailed overviews of the petrology of Hawaiian tholeiitic lava and Hawaiian alkalic lava are presented in Wright and Helz (chapter 23) and Clague (in press), respectively.

Volcano volume reflects the degree of melting of the tholeiitic basalt and probably also the size and frequency of intrusion of magma batches. The inverse correlation of volcano volume with $^3He/^4He$ ratio in tholeiitic basalt indicates that smaller percentage melts are derived from sources with more of the primitive component and larger percentage melts are derived from sources with less of the primitive component. Volcano volumes and compositions of the shield tholeiitic basalt are also related, less-enriched tholeiitic basalt forms larger shields and more-enriched tholeiitic basalt forms smaller shields (Clague and Frey 1979), although this correlation is imperfect. Models developed in the future should address the problem of characterizing the isotopic and trace-element compositions of the three mantle components and address the timing and processes of mixing of these sources. The source volumes inferred from different melting models must be considered. Wright's (1984) model requires only modest source volumes, whereas the model of Budahn and Schmitt (1984) requires partial melting of a mantle zone 100 km thick and 100 km wide to generate the volcanoes of the principal Hawaiian Islands. Such enormous inferred volumes of mantle source rock pose numerous problems for models advocating small-percentage melting to generate the tholeiitic shields.

A separate problem is the cause of the alkalic rejuvenated stage. Jackson and Wright (1970) used tide-gage data from Moore (1970) to suggest that generation of the rejuvenated-stage Honolulu Volcanics might be caused by uplift as Oahu has passed over the

Hawaiian Arch. They argued that the Hawaiian Arch, an isostatic response to volcanic loading on the oceanic crust, follows the progression of active volcanic centers by several hundred kilometers and several million years. Clague and others (1982) showed that the duration of the quiescent period preceding eruption of the rejuvenated-stage lava has decreased systematically from nearly 2.5 m.y. on Niihau to <0.4 m.y. at Haleakala (see fig. 1.6). They suggested that a new mechanism should be sought to explain the age data. We have reexamined the data and conclude that they are consistent with the model proposed by Jackson and Wright (1970) because the rate of volcanic migration is increasing. The rejuvenated stage follows the formation of the shield not by a constant time but by a constant distance. The rejuvenated-stage Koloa Volcanics on Kauai and Kiekie Basalt on Niihau began erupting during formation of the Koolau shield located 180–225 km to the southeast. Likewise, the Honolulu Volcanics on the Koolau Range of Oahu began erupting during formation of the East Maui shield located 160 km to the southeast. The rejuvenated-stage Kalaupapa Volcanics on East Molokai erupted during formation of the Mauna Kea shield located 200 km to the southeast. Finally, the rejuvenated-stage Hana Volcanics on East Maui began erupting during formation of the Mauna Loa shield, located 160 km to the southeast. In each case, the lava of the rejuvenated stage began erupting during formation of a large shield 190 ± 30 km to the southeast. The Hawaiian Arch is about 250 km from the center of the volcanic ridge, but only 210 km to the east-southeast of Hawaii (Walcott, 1970). It is therefore likely that a factor in magma generation during the rejuvenated stage is the rapid change from subsidence to uplift as the volcanoes override the flexural arch created by formation of large shields. To the northwest of the Hawaiian Islands the rates of volcanic propagation were slower and more constant; we predict that lava of the rejuvenated stage will postdate the shield stage by 2–3 m.y. We also suggest that the apparent paucity of lava from the rejuvenated stage to the northwest of the Hawaiian Islands may reflect the absence of large volcanic edifices capable of flexing the lithosphere sufficiently. Likewise, the absence of any lava samples of the rejuvenated stage from the Emperor Seamounts may result from the rather wide spacing between volcanic edifices: by the time the next younger volcano formed, the previously constructed volcano was already beyond the arch. The fact that the Emperor volcanoes were constructed on young, thin lithosphere would amplify this effect because the distance from the load to the flexural arch decreases as the lithosphere becomes less rigid.

FIXITY OF THE HAWAIIAN HOT SPOT

Wilson's original hypothesis for the origin of the Hawaiian and other island chains by passage of the crust over a source of lava in the mantle (Wilson, 1963a, b, c) did not require that the hot spot be fixed, only that it have some motion relative to the crust above it. Morgan (1972a, b), on the other hand, specified that a worldwide system of thermal plumes (hot spots) was fixed in the mantle and that the relative movement between them was small or negligible. Several workers (for example, Minster and others, 1974; Gordon and Cape, 1981; Morgan, 1981) have shown from relative plate motions and paleomagnetic and other data that Morgan's hypothesis of relative hot-spot fixity is basically correct, but that the fixity of the hot-spot frame of reference with respect to the spin axis, particularly in early Cenozoic and Late Cretaceous times, is not established.

PALEOMAGNETIC TESTS OF HOT-SPOT FIXITY

Age data along the chain have shown that there has been more or less continuous relative motion between the Hawaiian hot spot and the Pacific plate, thereby proving the kinematic aspect of the hot-spot hypothesis, but these data have little or no bearing on the question of hot-spot fixity. The lava flows that form volcanoes of the Hawaiian-Emperor Chain, however, contain a nearly continuous magnetic record of the latitude of the Hawaiian hot spot for the entire Cenozoic and the latest Cretaceous. Although only a small fraction of this magnetic record has been read, there are now sufficient data to provide a partial test of the fixity hypothesis for the Hawaiian hot spot. Paleomagnetic data from volcanoes along the chain show that the Hawaiian hot spot (and thus presumably the worldwide hot-spot frame) has been, to a first approximation, fixed with respect to the spin axis since the time of formation of the Hawaiian-Emperor bend. The limited data indicate, however, that there was motion between the hot spot and the spin axis, that is, true polar wander, before that time.

The paleolatitudes of several Hawaiian-Emperor volcanoes, as determined from paleomagnetic studies on individual rock samples and from shipboard magnetic surveys, are given in table 1.11 and plotted in figure 1.11 as a function of volcano age. In general, the data indicate that the Hawaiian-Emperor volcanoes formed not at their present latitudes but at a latitude near the present latitude of Hawaii. Thus, the latitude of the Hawaiian hot spot has been approximately fixed throughout the Cenozoic. The data are not of uniform quality, however, and some care must be exercised in their interpretation.

The paleomagnetic data have been discussed and evaluated by Jackson and others (1980), Kono (1980), and Sager (1984), who point out that the paleomagnetic sampling of Meiji, Nintoku, Ojin, Midway, Nihoa, and the Island of Hawaii involved a small number of lava flows, making it doubtful that the secular variation is adequately averaged out. The errors for the Ojin and Nintoku sites reflect this uncertainty, but there is reason to suspect that the errors assigned to the paleolatitudes of Midway, Meiji, and Nihoa are too small. This is because of the unusually low dispersions and the likelihood of serial correlation of some of the flows, which further decreases the number of independent measurements from the sites.

The paleolatitude of 17.5° ± 5°, determined for Suiko by Kodama and others (1978) from magnetic survey data, is suspect for several reasons. First, the magnetic anomaly over Suiko is complex, resulting in a low statistical test of fit ($R = 1.1$) for the inversion. Second, it is likely that Suiko is constructed from several coalesced volcanoes (Bargar and Jackson, 1974), possibly of different ages, and the necessary assumption of uniform magnetization is probably invalid for this seamount. In addition, the paleolatitude is inconsistent with that obtained from the paleomagnetic study of

TABLE 1.11.—*Paleolatitudes determined for volcanoes of the Hawaiian-Emperor Chain*

[From paleomagnetic measurements on lava flows and from shipboard magnetic surveys (SM). Data from compilations by Kono (1980) and Sager (1984); the more reliable data (Sager, 1984) underlined; uncertainties are the values of α_{95}]

Volcano		Number of flows determined	Present latitude (degrees north)	Paleolatitude (degrees north)
Number	Name			
1,2,4,	Kilauea, Mauna Loa Hualalai (historical)	17	19.5	19.6±1.4
1,2,3	Kilauea, Mauna Loa Mauna Kea(^{14}C dated)	8	19.5	17.7±10.7
12	Koolau	33	21.4	16.8±3.6
13	Waianae	55	21.5	15.7±3.3
14	Kauai (Makaweli Member, Waimea Canyon Basalt)	25	22.0	15.6±3.1
14	Kauai (Napali Member, Waimea Canyon Basalt)	46	22.1	14.9±3.1
17	Nihoa	14	23.1	21.0±6.6
52	Midway	13	28.2	15.4±5.4
65A	Abbott	(SM)	31.8	17.5±2.4
81	Ojin	6	38.0	17.6±13.2
86	Nintoku	4	41.3	36.0±24.6
91	Suiko	(SM)	44.8	16.7±5
91	Suiko	65	44.8	27.1±3.5
108	Meiji	6	53.0	19.2±4.1

Suiko (Kono, 1980), which is the best study of its kind for any of the volcanoes in the chain.

Sager (1984) included in his compilation two additional determinations from the principal Hawaiian Islands that we have chosen to omit from table 1.11. These include a group of 129 flows from the Islands of Hawaii and Niihau, and a second group of 19 flows from Kauai. Both groups include flows from the rejuvenated stage that were erupted several million years after the hot spot had moved (relatively) southeastward to form new tholeiitic shields. Although both of these determinations were included by Sager in his list of more reliable paleolatitudes, they are so close to the present position of the hot spot that their elimination has no significant impact on the conclusions drawn from the data.

Taken at face value, the more reliable paleolatitude data (fig. 1.11) indicate that the Hawaiian hot spot may have been a few degrees south of its present position during the late Cenozoic, near its present position when Abbott Seamount formed at about 39 Ma, and 7° north of its present position at Suiko time, 65 Ma. Analyses of paleoequator (Sager, 1984) and worldwide paleomagnetic data (Livermore and others, 1983), however, show that there has been little or no motion of the spin axis relative to the worldwide hot-spot frame during the past 40 m.y. or so. From this comparison of independent data Sager (1984) concluded that the apparent southward displacement of the Hawaiian hot spot shown by the data from younger volcanoes in the chain (fig. 1.11) reflected changes in the magnetic field rather than relative movement between the hot spot and the spin axis.

The apparent displacement indicated by the Suiko data, however, is probably real. The Suiko paleolatitude is based on analysis of a large number of flows (table 1.11) recovered by coring over an interval of 550 m (Kono, 1980). Even when certain flows thought to represent a very short time interval are grouped, there are still a minimum of 40 independent data. There are also 12 places in the cores where the inclination changes by more than 15°, which indicates that at least 13 secular variation cycles have been sampled, making it likely that secular variation has been adequately averaged out. Other paleomagnetic stability indices indicate that 27.1°±3.5° is a highly reliable measure of the latitude of formation of Suiko Seamount (Kono, 1980).

BIOFACIES AND TEMPERATURE DATA FROM THE HAWAIIAN-EMPEROR CHAIN

Although northward displacement of the Hawaiian hot spot relative to the spin axis is only indicated by the single paleolatitude from Suiko, it is supported by a variety of additional data. Analysis of Pacific deep-sea sediment cores, for example, shows that the paleoequator was 10°–16° farther north than at present between about 75 Ma and 65 Ma (Sager, 1984).

Biofacies data from DSDP Leg 55 drilling in the Emperor Seamounts provide semiquantitative substantiation of the Suiko paleolatitude. The bioclastic sediment on Suiko, Nintoku, and Ojin Seamounts consists primarily of coralline algae and bryozoans with ostracodes, foraminifers, and assorted shell fragments typical of a shallow-water, high-energy environment (Jackson and others, 1980). Only a single coral was found in the Suiko material, and none was recovered from either Ojin or Nintoku, indicating that corals were not significant contributors to the carbonate buildups.

Schlanger and Konishi (1975) have pointed out that carbonate buildups in the Pacific can be divided into bryozoan-algal and coral-algal facies, the distribution of which depends largely on water temperature and solar insolation and thus is, to a large degree, a function of latitude. They observe that in the modern Pacific, the coral-algal facies dominates at latitudes less than about 20°, whereas the bryozoan-algal facies is predominant above about 30° latitude. They locate the boundary between these facies at about 25° latitude, but emphasize that the transition is gradual. In the central Pacific, the annual surface-water temperature at 25° latitude is about 22 °C (Muromtsev, 1958), which is usually considered the minimum for active coral-algal reef growth (Vaughn and Wells, 1943; Heckel, 1974). The optimum temperature for vigorous reef growth is 25–29 °C. Thus, the existence of carbonate buildups of the bryozoan-algal facies atop Ojin, Nintoku, and Suiko Seamounts indicates that the reefs atop the volcanoes formed in water temperatures less than about 22 °C.

Using the oxygen-isotope temperature data of Savin and others (1975) for the North Pacific, Greene and others (1978) reconstructed the approximate latitude variation through time for the 20 °C and 22 °C isotherms (fig. 1.12). They showed that if the Hawaiian hot spot were fixed, then Suiko Seamount would have formed in water warm enough to have developed active coral-algal reefs. Following the analysis of Greene and others (1978), Jackson and others (1980) showed that the Paleocene water temperature at the latitude determined by the paleomagnetic data from Suiko was appropriate for the bryozoan-algal carbonates that occur immediately above the basalt.

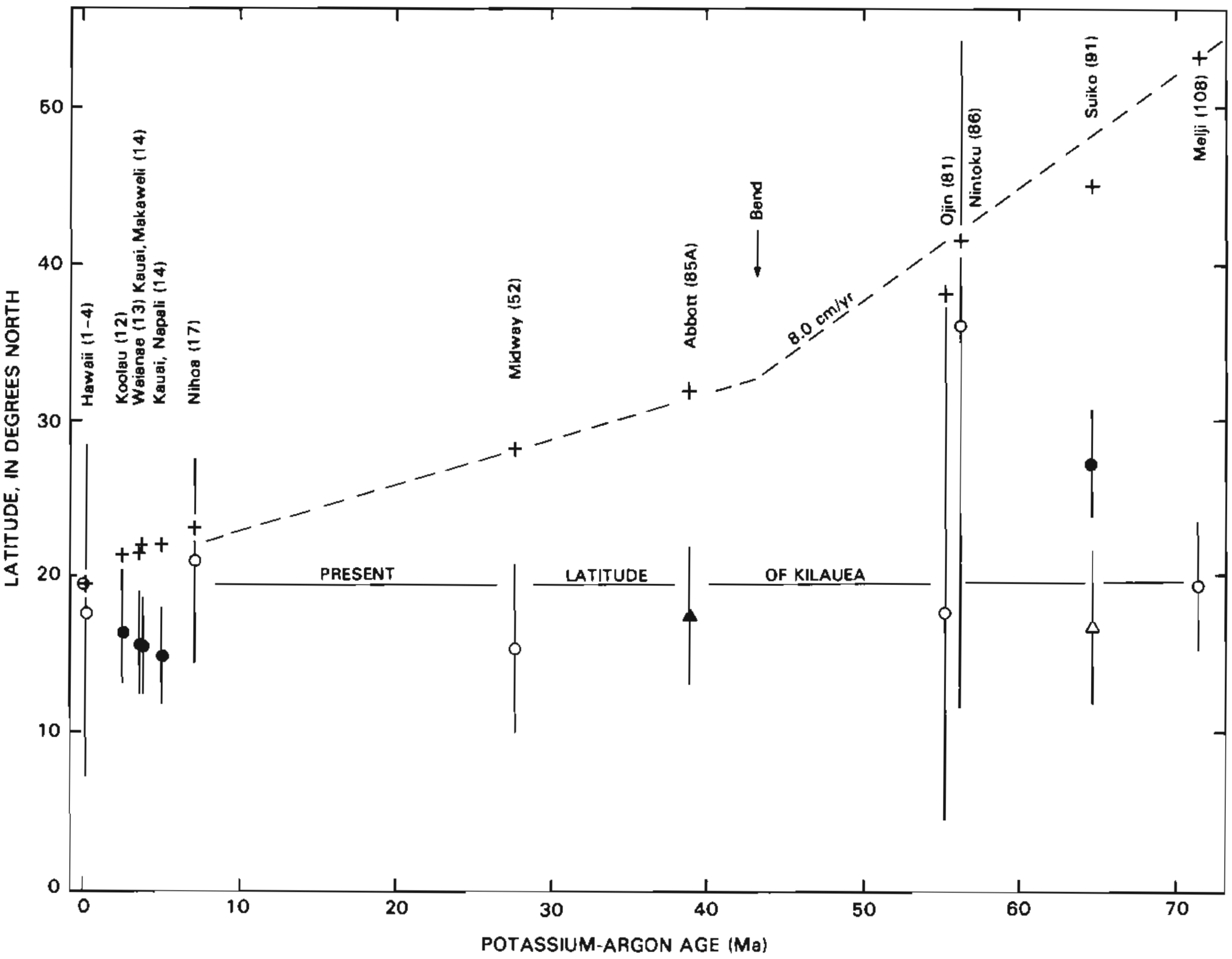

FIGURE 1.11.—Paleolatitude plotted against age for volcanoes along Hawaiian-Emperor Chain. Crosses, present latitude; dots and circles, paleolatitudes determined from paleomagnetic data; triangles, paleolatitudes determined from shipboard magnetic surveys. More reliable data indicated by solid symbols. Error bars show α_{95}. Dashed reference line is backtracked position of hot spot relative to Pacific plate assuming a constant velocity of 8 cm/yr. Paleomagnetic data from table 1.11, age data from table 1.4 and appendix 1.1.

The paucity of coral material on seamounts in the central Emperor Chain is in contrast to Koko and the seamounts on the bend, where corals are more common but still less abundant than in a region of vigorous coral reef growth (Davies and others, 1971, 1972; Matter and Gardner, 1975). Oxygen-isotope temperatures of carbonate diagenesis for Suiko, Nintoku, Ojin, and Kammu Seamounts (McKenzie and others, 1980) show a gradual warming from Suiko to Koko, at least in part caused by southward migration of the hot spot (Jackson and others, 1980). Thus, the biofacies and paleotemperature data from Leg 55 are consistent with the paleomagnetic data, indicating a latitude of 27° for the hot spot at Suiko time. The data are also consistent with Sager's (1984) suggestion that the hot spot had reached its approximate present latitude by the time Abbott Seamount formed just after formation of the Hawaiian-Emperor bend; the slightly cooler temperatures indicated by the carbonate facies and temperature data from the bend seamounts are probably related to the sudden drop in ocean temperature in the late Eocene rather than to a more northerly hot spot.

Thus, the paleomagnetic data from Suiko, the biofacies and temperature data from the central and southern Emperor Seamounts, and the Pacific paleoequator data all indicate southward migration of the Hawaiian hot spot in the early Tertiary and Late Cretaceous. This conclusion is consistent with previous findings, based on analysis of worldwide paleomagnetic data in the hot-spot frame of reference, of about 10° of southward movement of the hot-spot frame relative to the spin axis (that is, true polar wander)

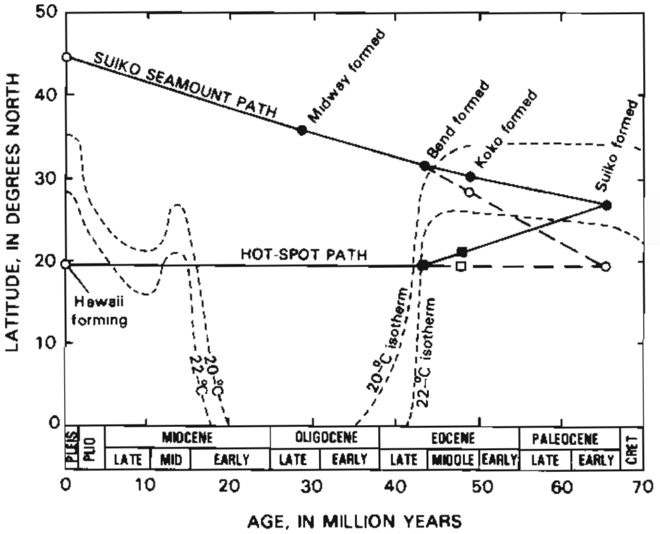

FIGURE 1.12.—Approximate position of 20 °C and 22 °C surface-water isotherms in north-central Pacific during Cenozoic, modified from Greene and others (1978), based on data of Savin and others (1975). Dots, paleolatitudes of Suiko Seamount assuming that Suiko formed at 27° N. and that hot spot has been fixed since time of bend formation. Circles, paleolatitudes for Suiko assuming a fixed hot spot for past 65 m.y. Squares, positions of formation of Koko Seamount and bend under same assumptions. Backtracking was about an Emperor pole at lat 17° N., long 107° W. and a Hawaiian pole at lat 69° N., long 68° W. (Clague and Jarrard, 1973). The 22 °C isotherm is approximate boundary between coral-algal (warmer) and bryozoan-algal (colder) facies of Schlanger and Konishi (1975).

during the latest Cretaceous and earliest Tertiary (for example, Gordon and Cape, 1981; Jurdy, 1981, 1983; Morgan, 1981; Gordon, 1982).

The paleolatitude of 17.5°±4.4° N. found for Abbott Seamount puts the Hawaiian hot spot at about its present latitude by 40 Ma, which is consistent with the conclusion of Livermore and others (1983) that true polar wander did not occur during the past 35 m.y. The paleoequator analysis of Sager (1984) suggests that there was no true polar wander after formation of the bend, that is, after 43 Ma. This requires approximately 7.6° of southward latitudinal motion of the hot spot between 65 Ma and 43 Ma and 5° of northward motion of the Pacific plate in order to satisfy the relative motion of about 0.65° latitude per million years indicated by the age-distance data.

COMPARISON TO OTHER PACIFIC LINEAR ISLAND CHAINS

Another way of evaluating the movement of hot spots is to compare the orientation and age progression quantitatively along volcanic chains formed during the same time period on the same plate. Several studies (Clague and Jarrard, 1973; Jackson, 1976; Jarrard and Clague, 1977; Epp, 1978; McDougall and Duncan, 1980; Turner and others, 1980; and Duncan and Clague, 1985) have attempted such evaluations for the Pacific plate since Morgan (1971) first proposed the technique. Most of the linear volcanic chains in the Pacific basin are oriented roughly west-northwest and apparently formed sequentially over nearly stationary hot spots during the last 43 m.y. as the Pacific plate rotated clockwise about a pole located near lat 69° N., long 68° W. (Clague and Jarrard, 1973). Another group of linear chains exhibit roughly north-trending orientations and apparently formed by the same mechanism between at least 80 Ma and 43 Ma as the Pacific plate rotated clockwise about a pole located near lat 17° N., long 107° W. (Clague and Jarrard, 1973).

The hot spots that formed the Hawaiian, Austral-Cook, Society, Marquesas, Caroline, Pitcairn-Gambier, Samoan, and Islas Revilla Gigedos island chains and the Pratt-Welker and Cobb-Eickelberg seamount chains moved very little with respect to one another (Duncan and Clague, 1985). The most convincing evidence that hot spots move with respect to one another comes from the orientation of the Marquesas Islands, which is discordant by about 25° with that predicted, implying motion of the Marquesas hot spot to the northeast with respect to the hot-spot reference frame at several centimeters per year (Jarrard and Clague, 1977) during the last 5 m.y. The rates of volcanic migration along the chains younger than 43 Ma fit a pole of rotation at lat 68° N., long 75° W. and an angular rotation rate of 0.95°±0.02°/m.y. (Duncan and Clague, 1985).

CAUSE OF THE HAWAIIAN-EMPEROR BEND

An especially knotty problem over the past decade has been the relationship between Pacific sea-floor spreading, worldwide plate motion, and the Hawaiian-Emperor bend. Since there is now firm evidence that the motion of the hot-spot frame was small during the early Cenozoic and has been negligible since then, the 120° angle in the Hawaiian-Emperor bend must represent a major (circa 60°) change in the absolute motion of the Pacific plate. Since the motions of individual plates are not independent, we would expect such a significant change to be part of a worldwide reorganization of both absolute and relative plate motions. Various authors have suggested that the bend might correlate with circum-Pacific tectonic events (Jackson and others, 1972; Clague and Jarrard, 1973; Moore, 1984), that it may be caused by the collision of India and Eurasia (Dalrymple and Clague, 1976), or that it may be the result of new subduction zones along the southwestern margin of the Pacific plate (Gordon and others, 1978). However, completely satisfactory correlations have not been achieved.

A major feature of the northeast Pacific magnetic-anomaly pattern is the major change in the trend of the magnetic anomalies, that is, the magnetic bight, between anomalies 24 and 21. Reconstruction of the Pacific plate shows that this change in the anomaly pattern is the result of a change in spreading about the Pacific-Kula-Farallon triple junction, in particular the cessation of spreading on the Kula Ridge (Scientific Party DSDP 55, 1978; Byrne, 1979). This occurred perhaps as early as anomaly 24 but no later than the time of anomaly 21, which is approximately the time of the major change in spreading direction between Greenland and Europe (Vogt and Avery, 1974) and shortly before an apparent increase in the frequency of geomagnetic reversals (Jacobs, 1984). The change in anomaly orientation can also be correlated with numerous events associated with worldwide reorganization of plate motions (Rona and Richardson, 1978).

The early magnetic time scales of Heirtzler and others (1968) and LaBreque and others (1977) put anomaly 21 at about 54–53 Ma and 52–51 Ma (corrected for new K decay and abundance constants), respectively, which implies a lag of at least 10 m.y. between the reorganization of Pacific magnetic anomalies and the formation of the Hawaiian-Emperor bend at 43.1 ± 1.4 Ma (Dalrymple and Clague, 1976). More recent time scales, however, have narrowed this somewhat awkward gap. Ness and others (1980) put anomaly 21 at about 49–48 Ma, Lowrie and Alvarez (1981) at about 48.5–47.5 Ma, and Butler and Coney (1981) at about 47–46 Ma. As suggested by Butler and Coney, a lag of 3–4 m.y. is close enough to suggest a causal relationship between the relative motion change represented by the magnetic bight and the absolute change represented by the Hawaiian-Emperor bend.

Gordon and others (1978) suggested that the change in direction of the Pacific plate at ~43 Ma was caused by the development of new trenches along the southwestern boundary of the plate. These new trenches, which replaced an earlier set of ridges and transform faults, were the result of rifting of Australia from Antarctica and the accompanying convergence of the Australia-Indian and Pacific plates. Gordon and others (1978) suggest that some time would have elapsed before the subducting plate would have been long enough and dense enough to exert sufficient torque on the Pacific plate to change its direction of motion. This could explain the lag between the timing of reorientation of the magnetic anomalies, which record the change in relative plate motion, and the age of the Hawaiian-Emperor bend, which records the change in absolute plate motion. The duration of the lag time would depend on the rate of plate convergence. As noted by Gordon and others (1978) a lag time of perhaps as much as 10 m.y. might be explained if convergence were sufficiently slow. Their mechanism is more plausible, however, if the lag can be shortened to a few million years, as now seems likely.

HAWAIIAN HOT-SPOT MODELS

Although there is now little doubt that the Hawaiian-Emperor Chain owes its origin to a hot spot that has been approximately fixed with respect to the Earth's spin axis throughout the Cenozoic, there is scant information concerning the exact mechanism involved. Even the term "hot spot" may be misleading, for excess heat is not necessarily involved. Alternatively, it could be the result of pressure release in a mantle source area (Green, 1971; McDougall, 1971; Jackson and others, 1972).

A successful hypothesis for the Hawaiian hot-spot mechanism must explain the propagation of volcanism along the chain, the near-fixity of the hot spot, the chemistry and timing of the eruptions from individual volcanoes, and the detailed geometry of volcanism, including volcano spacing and departures from absolute linearity. Over the past decade or so several mechanisms have been advanced to explain how a linear chain of volcanoes might be progressively erupted onto the sea floor, but most are highly generalized and suffer from lack of detail. Few of the hypotheses address all of the kinematic and petrological issues, and none seems to be amenable to experimental test. Nonetheless, they are interesting speculations on solutions to an extremely difficult problem.

All of the proposed mechanisms can be grouped into four basic types:

1. Propagating fracture driven by lithospheric stresses.
2. Thermally or chemically driven convection.
3. Melting caused by shear between the lithosphere and the asthenosphere.
4. Mechanical injection of heat into the lithosphere.

PROPAGATING-FRACTURE HYPOTHESES

Dana (1849) was the first to associate the Hawaiian volcanic chain with crustal fracturing. He proposed that the Hawaiian and other volcanic chains in the Pacific were each emplaced along a series of short echelon fractures (or "rents") that were widest at the southeast end where volcanism was the most prolonged. He considered these fractures to be part of a worldwide system reflecting tension in the crust resulting from cooling of the Earth from an initially molten state. S. Powers (1917) agreed that the eruptions occurred through a superficial set of echelon fractures following the trend of the chain, but he attributed the trend to some deeper seated lines of weakness. Chubb (1934) thought that the Hawaiian swell represented the surface manifestation of a broad anticline trending in the direction of the chain and produced by compression oriented north-northeast and south-southwest. He proposed that the Hawaiian volcanoes erupted along strike faults and dip faults atop and aligned with the anticline.

Betz and Hess (1942) found no evidence of vertical displacement along fault scarps but thought that the chain might be the manifestation of a great transcurrent strike-slip fault resulting from crustal shortening within the Pacific basin caused by Tertiary volcanism along the margins of the basin. In view of the Earth's sphericity, the straightness of the chain indicated to them that the fault plane was essentially vertical. Considering the strength and thickness of the ocean crust, they thought that an anticline the dimensions of the Hawaiian swell was unlikely and proposed instead that the swell represented a thick lava pile related to the presumed fault zone. Dietz and Menard (1953) thought this idea improbable because of the enormous volume of lava that would be required to produce the swell.

Other early authors subscribed to the idea that the Hawaiian Chain developed atop a propagating fracture (for example, Stearns, 1946; Eaton and Murata, 1960; Jackson and Wright, 1970), but they were vague or noncommital as to the cause of the rupture.

Most recent authors who have advanced propagating-fracture hypotheses have attempted to relate the cause of the fracture to either local or regional stress fields within the Pacific plate. Green (1971) suggested that divergent flow vectors caused by the movement of the plate over an imperfect sphere, that is, an uneven upper mantle surface, caused local tension and intermittent failure of the lithosphere. The fracturing would allow rapid upwelling and partial melting of material from the low-velocity zone. One problem with this hypothesis is the means by which the irregularities on the asthenosphere are maintained, but Menard (1973) suggested that such persistent asthenospheric "bumps" might be caused by a rising thermal plume in the mantle.

McDougall (1971), following the ideas of Green (1971), proposed that the physical feature that subjected the plate to local tension might be either a thermal high or an incipient upwelling caused by a local concentration of heat-producing radioisotopes. According to McDougall's model, fracturing results in the diapiric rise of peridotitic material from the asthenosphere into the lithosphere (fig. 1.13*A*, *B*), where partial melting then generates tholeiitic magma. Movement of the plate and counterflow of the asthenosphere eventually decapitate the diapir, but replacement of material from deeper levels of the asthenosphere perpetuates the high and a new diapir is created (fig. 1.13*C*, *D*). Noting that the rate of propagation of volcanism along the Hawaiian Chain is slightly more than twice the half-spreading rate of the East Pacific Rise, McDougall concluded that there must be counterflow of material in the asthenosphere in a zone of thickness comparable to that of the lithosphere. Jackson and others (1980) showed that it was not possible to reconcile equal-but-opposite hot-spot motion with the paleolatitude of Suiko Seamount if the counterflow had persisted throughout the history of the Hawaiian-Emperor Chain. Hot-spot countermovement until the time of the bend followed by latitudinal stability from then to the present is, however, kinematically permissible.

Another mechanism for producing a local stress field and lithospheric rupture was proposed by Walcott (1976), who related the stress to the volcanic load on the lithosphere. He suggested that large volcanoes will produce lithospheric stresses during growth that may be large enough to cause disruption of the plate. If the plate is under a normal state of horizontal compression, then the failure of the lithosphere will occur preferentially parallel to the direction of the compressive stress. The direction of rupture will remain linear as long as the ambient stress direction remains constant, and the rate of propagation will depend on the speed of formation of the load. Noting the rapidity with which Hawaiian volcanoes form, Walcott concluded that the propagation of volcanism along the Hawaiian chain must be limited by the availability of magma source material. Thus, the mechanism would be self-perpetuating and self-regulating. Although this mechanism will result in a line of volcanoes, it does not explain the observed age progression nor does it account for hot-spot fixity, but it might be locally important and explain the detailed distribution of volcanoes within the Hawaiian Chain (Walcott, 1976).

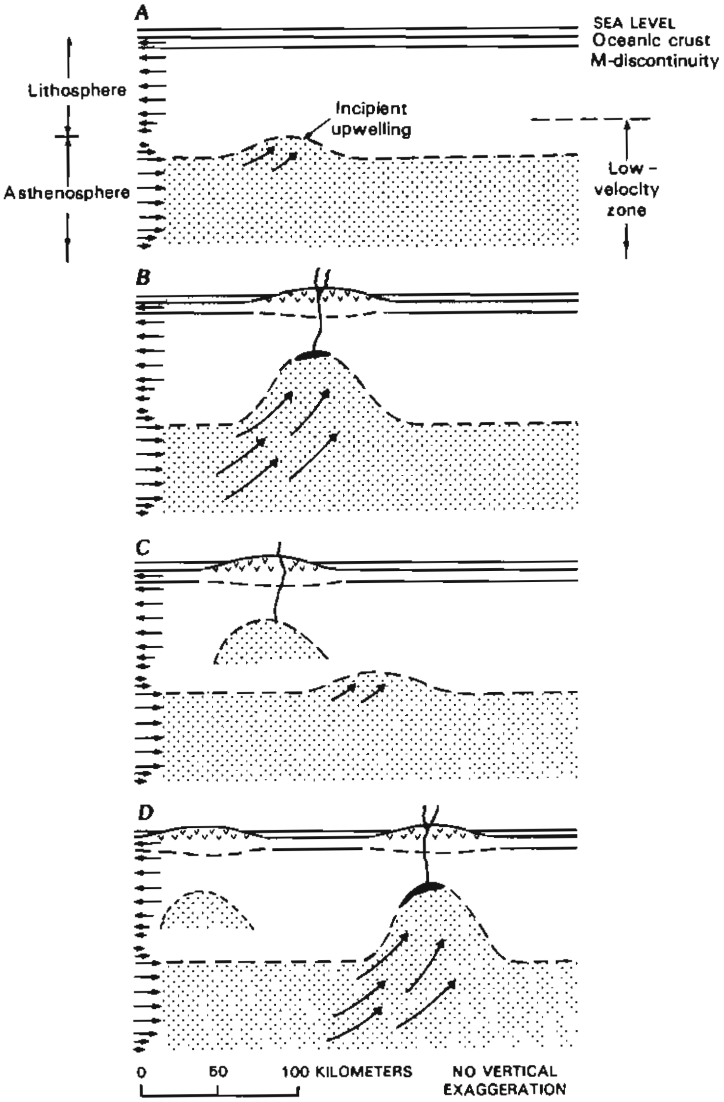

FIGURE 1.13.—Schematic diagram of McDougall's (1971) propagating-fracture hypothesis. Propagating tensional fracture allows diapiric upwelling from asthenosphere (*A*) and partial melting (*B*). Relative motion between lithosphere and asthenosphere (arrow along left margin) eventually decapitates diapir (*C*) and cycle begins at a new position (*D*). The shaded zone represents peridotitic material that is the source rock of the lava. From McDougall.

Expanding on the original idea of Dana (1849), Jackson and others (1972) observed that the individual volcanic centers of the Hawaiian-Emperor Chain appear to lie on short, sigmoidal, overlapping loci that are echelon in a clockwise sense in the Hawaiian Chain and in a counterclockwise sense in the Emperor Chain (fig. 1.14), although the latter was based on inadequate bathymetric data. They proposed that the pattern of loci may be caused by extensional strain resulting from tension within the Pacific plate, but they did not speculate on the ultimate cause of the stresses. Jackson and Shaw (1975) developed this idea more fully and extended it to other chains in the Pacific. They argued that linear hot-spot chains track and record the states of stress in the Pacific plate as a function of time, and that the stress was reflected in the detailed geometry of volcanoes within a chain, that is, in the orientation of the volcanic loci, which represent the injection of magma along lines perpendicular to least principal stress directions. On the basis of their analysis of the Hawaiian-Emperor, Pratt-Welker, Tuamotu, and

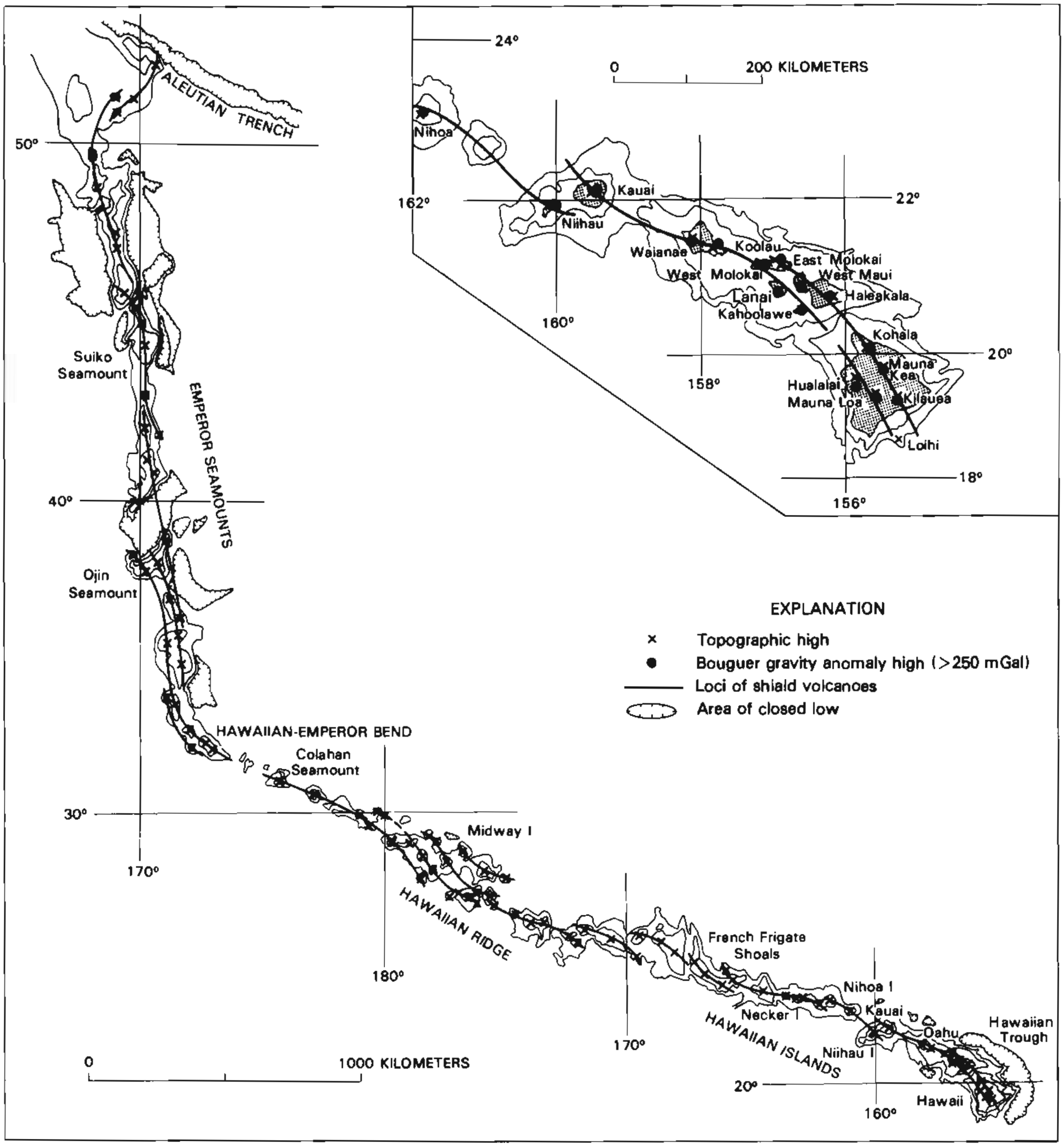

FIGURE 1.14.—Loci of shield volcanoes in Hawaiian-Emperor Chain according to Jackson and others (1972). Inset shows detailed relation between topographic highs, Bouguer gravity anomaly highs, and loci for principal Hawaiian Islands. Contour interval is 1 km; hachures indicate area of closed low.

Austral-Ellice-Gilbert-Marshall Chains, they concluded that the stress orientations since the time of formation of the Hawaiian-Emperor bend were caused by a right-lateral rotational couple acting within the plane of the Pacific plate. This couple resulted in the minimum principal stress oriented in a northeast-southwest direction. Before the time of the bend, the rotational couple was left-lateral and the minimum stress was oriented north-northwest and south-southeast. The curvature in the volcanic loci, they proposed, reflects episodic swings of the minimum-stress directions that averaged about 12 m.y. per episode and were perhaps a consequence of episodic changes in the force vectors at plate boundaries. Jackson and Shaw (1975) were uncertain about the exact causes of the stress field within the Pacific plate, but noted that possible contributors included convergence and divergence at plate boundaries, varying convection rates in the asthenosphere, and volume changes within the plate resulting from changing pressure and temperature.

On the basis of an analysis of volcano spacing and the relation of volcanic chains to preexisting plate structures, Vogt (1974) suggested that the factors that controlled the path of hot-spot chains are not clearly of one origin, but included simple shear, reactivated sea-floor-spreading structures, and local stresses. He concluded that the sigmoidal loci (fractures) postulated by Jackson and others (1972) for the Hawaiian Chain had no counterpart in other chains, although Jackson and Shaw (1975) claimed to have found a similar pattern on other chains in the Pacific.

Solomon and Sleep (1974) preferred the propagating-fracture hypothesis, in part because it avoided the necessity of an abnormal and unknown source of heat in the asthenosphere. They emphasized that the stresses in the Pacific plate can be explained entirely in terms of the forces acting on plate boundaries, and that such mechanisms have the attractive feature of being amenable to numerical treatment. They proposed that the continued motion of the plate with respect to the boundary force field and to secondary convection cells in the asthenosphere might cause a linear propagating fracture as new parts of the plate moved into zones of tension, and that such a tensional fracture would permit the passive upwelling of volcanic material from below. This model offers no explanation why Hawaii is located where it is. In addition, passive mantle upwelling seems inadequate to produce the enormous volume of lava that comprises the Hawaiian Islands.

Turcotte and Oxburgh (1973, 1976, 1978) also subscribed to propagating tensional fractures as a possible cause of linear midplate volcanism. They noted that although brittle failure may occur at the surface of a plate, plastic failure is more likely at depth where lithostatic pressure is large compared with the yield stress. Theoretically, plastic and brittle failure will occur at angles of 35° and 45°, respectively, to the direction of tension (fig. 1.15*A*). Possible causes of tension include thermal stresses in the cooling and thickening plate as it moves outward from the spreading ridge and membrane stresses caused by the movement of plates on the surface of the nonspherical Earth (fig. 1.15*B*, *C*). Turcotte and Oxburgh note that the angle between the Hawaiian Chain and the direction of sea-floor spreading, as deduced from magnetic anomalies and fracture zones, is 34°, in good agreement with the predicted value. They also note that the angle between the trend of the chain and the

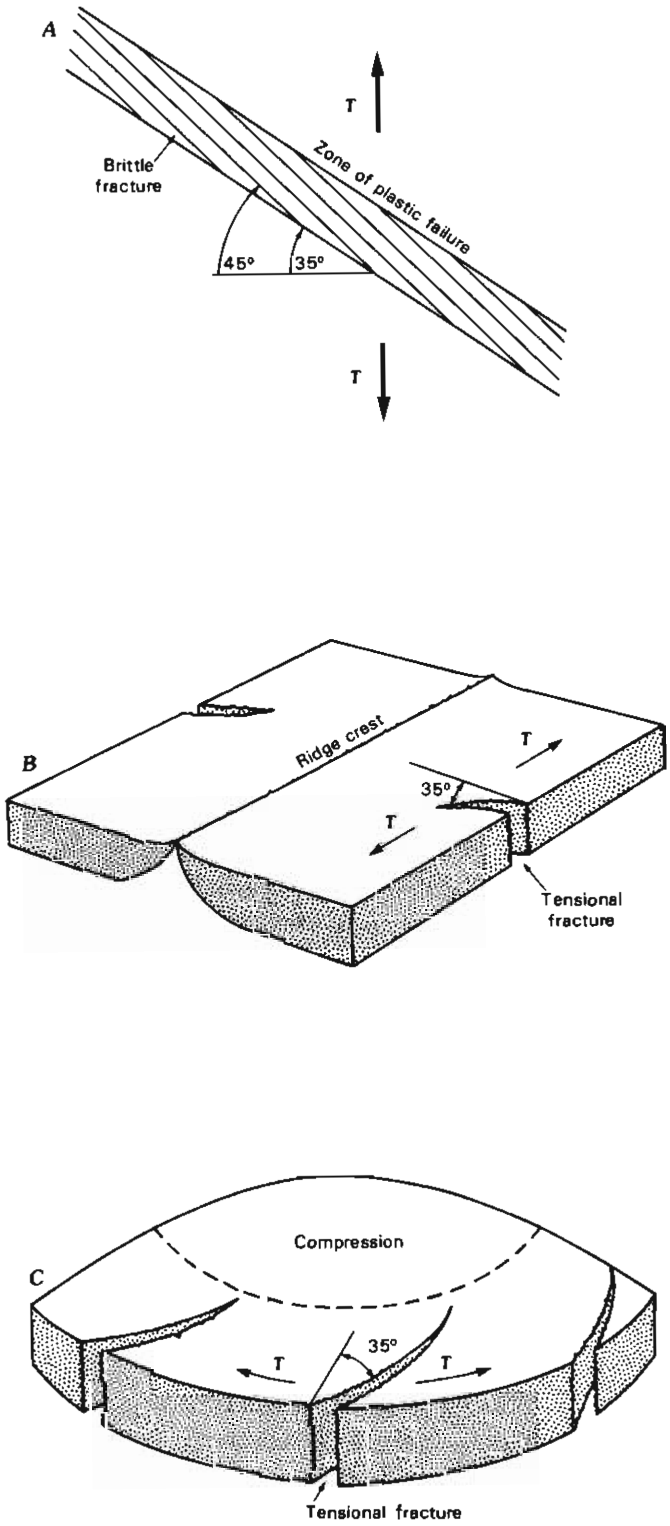

FIGURE 1.15.—Tensional stresses as a possible cause of propagating fractures in lithospheric plates. ***A***, Orientation of plastic and brittle failure in thin plate under tension (*T*) according to Turcotte and Oxburgh (1973, 1976, 1978). ***B***, Fracture in lithospheric plate from tensional stress caused by cooling and thickening of plate away from spreading ridge. ***C***, Fracture caused by membrane stresses in northward-moving plate on oblate Earth.

loci of Jackson and others (1972) is approximately correct for brittle fracture. The Cook-Austral, Tuamoto-Pitcairn, and Kodiak-Bowie Chains also lie at angles of between 31° and 42° to spreading directions, but the angle made by the Marquesas is 60°, which is much larger than that predicted by Turcotte and Oxburgh (1978).

Both plastic and brittle failure, as proposed by Turcotte and Oxburgh, provide a means of propagating a fracture as a function of plate motion and might account for some degree of hot-spot fixity. The thermal mechanism relies on cooling and thickening of the plate as a function of time and distance from the spreading ridge. Once started, the fracture will propagate from a point that remains at a fixed crustal age from the ridge. As these authors point out, fractures due to membrane stresses would be most likely in middle latitudes because the change in the radius of curvature of the Earth is a maximum at a latitude of about 45°. For a plate in the northern hemisphere moving northward, the fracture would propagate southward from a point that remains latitudinally fixed. This mechanism does not, however, account for the great variety of latitudes of active Pacific hot spots, the parallelism of Pacific volcanic chains, or the Hawaiian-Emperor bend (Solomon and Sleep, 1974).

Handschumacher (1973) advanced three fracture-related explanations for the Emperor Seamount Chain, but he did not extend them to include the Hawaiian Chain. Two of the mechanisms, extrusion along a strike-slip fault and interaction between a stable part of the Pacific plate on the west and a spreading ridge on the east, have since been disproved by the age progression (younger southward) of the Emperor volcanoes. The third mechanism, secondary activity along a zone of weakness between eastern and western parts of the plate, invokes preexisting structural control, but, like all propagating fracture hypotheses, does not provide any insight into the lava-producing mechanism.

THERMAL AND CHEMICAL CONVECTION HYPOTHESES

Numerous authors have associated the Hawaiian Chain with thermally driven convection in the asthenosphere. Among the earliest were Dietz and Menard (1953) and Menard (1955), who hypothesized that the Hawaiian Arch or swell occurred over the intersection of two upwelling and diverging convection cells. This would put the lithosphere under tension and produce fracturing as the volcanic load increased, providing a reasonable explanation for the geometry and form of the Hawaiian Arch, Ridge, and Deep. It does not, however, account for the constant rate of propagation of volcanism along the chain, although in 1955 this was poorly known. Although he did not discuss the Hawaiian Chain, Wilson (1962) showed it to be coincident with an early Tertiary ridge which he suggested formed by diverging convection cells.

Wilson (1963a, b, c, d) was the first to suggest a thermal convection mechanism that specifically addressed the age progression in the Hawaiian and eight other parallel chains in the Pacific. He speculated that the source of lava resided in the stagnant, or at least more slowly moving, region of a mantle convection cell (fig. 1.16). Spreading of the sea floor above this fixed source would result in an age-progressive chain of volcanoes. Wilson (1963a) tentatively put the source at a depth of about 200 km, below the low-velocity zone, but did not speculate on the ultimate cause of the lava source.

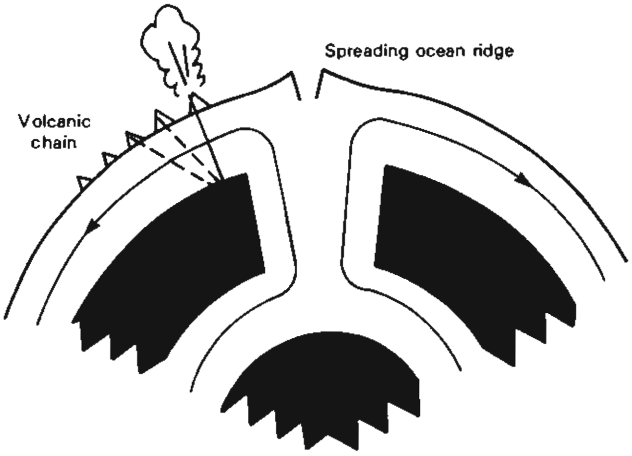

FIGURE 1.16.—Wilson's proposed possible origin of Hawaiian Chain. If lava is generated in stable core of mantle convection cell and surface is carried along by plate motion, then one source can give rise to a chain of successively extinct volcanoes. Modified from Wilson (1963), by permission of the National Research Council of Canada.

The hypothesis that has undoubtedly received the most attention since Wilson's is that of Morgan (1971, 1972a, b) who proposed that the Hawaiian and other Pacific hot spots were narrow thermal zones of upwelling, which he termed "plumes," that originate deep within the Earth's mantle, possibly near the core. They arise because of thermal instabilities (excess heat), which cause upward convection of hot plumes of mantle rock in much the same way that thermal instabilities in the atmosphere cause thunderhead clouds. According to this hypothesis, the plumes are of relatively low viscosity, about 150 km in diameter, and convect upward at a rate of about 2 m/yr. In addition to providing lava for volcanic chains, plumes are considered by Morgan to be a driving force of plate tectonics, to be capable of rifting continents, and to occur on midocean ridges as well as in the middle of plates. Morgan identified about 20 hot spots, but subsequent authors have tended to be more generous (for example, Burke and Wilson, 1976; Crough, 1983).

One aspect of Morgan's hypothesis that has proven extremely important to the study of plate tectonics, whether or not hot spots are actually plumes, is the concept that hot spots are fixed relative to one another and to the Earth's spin axis. As we discussed earlier, hot-spot fixity appears to be generally true for long periods of geologic time, and thus hot spots provide a stable reference frame for studies of absolute plate motions.

Morgan (1972a, 1972b) observed that most hot spots were characterized by a positive gravity anomaly and a topographic high, both of which, he said, are symptomatic of rising thermal currents in the mantle. Morgan calculated that as few as 20 plumes could bring up from depth an estimated 500 km^3/yr of mantle material and half of the total heat flow from the Earth.

Wilson (1973) endorsed the plume hypothesis and likened plumes to other natural diapiric mechanisms such as salt domes, thunderheads, and volcanic pipes. Menard (1973) noted that the Hawaiian, Austral-Cook (Macdonald Seamount), and Gulf of Alaska hot spots all lie on the updrift side of asthenospheric bumps and concluded that equally persistent rising plumes were required to sustain the asthenospheric relief at sites not associated with hot spots. Strong (1974) noted that the compositions of Kilauea and Mauna Loa lava were not the same, concluded that the Hawaiian plume was probably not the direct source of lava, and questioned whether Morgan's plumes were necessarily zones of mass transport. Alternatively, he suggested they might be zones of high thermal conductivity or concentrated diffusion.

Morgan (1972b) proposed four tests of the plume hypothesis, including seismic detection, prediction of plate motions from plume dynamics, evaluation of the necessity of plumes for heat transport from the deep mantle, and correlation of changes in Cenozoic and Cretaceous spreading patterns with the disappearance or emergence of new hot spots. Of the four, only the seismic test had any real potential for yielding a conclusive answer. Davies and Sheppard (1972), Kanasewich and others (1972, 1973), and Kanasewich and Gutowski (1975) analyzed seismic rays passing beneath the Hawaiian Islands from earthquakes in the southwest Pacific. They concluded that there is a zone of abnormally high velocities near the core-mantle boundary beneath Hawaii and that the seismic data are generally consistent with Morgan's plume hypothesis, although there were no data indicating an extension of the velocity anomaly upward through the upper mantle. The interpretation of the seismic data was questioned by Wright (1975) and Green (1975), who concluded that the observed travel time anomalies were most likely the result of upper mantle inhomogeneities beneath the seismic detector arrays in western North America. From a study of teleseismic arrivals from 55 earthquakes recorded at 21 stations on Hawaii, however, Ellsworth and others (1975) found evidence of lower than average velocities at depths of 30–50 km beneath the island. Whether this anomaly extends into the asthenosphere is unknown. Thus, the seismic evidence for a thermal plume beneath Hawaii appears to be, at best, inconclusive.

One difficulty with the plume hypothesis is that narrowly confined convection is unstable in fluids with high Prandtl numbers (kinematic viscosity divided by thermal diffusivity) such as mantle material (Turcotte and Oxburgh, 1978). Narrow plumes might be sustained, however, if confined to the upper mantle and heated from below by a lower mantle source (Turcotte and Oxburgh, 1978). Another problem is that the amount of partial melting that would result from the adiabatic decompression of mantle material rising from the core-mantle boundary is much too high to result in Hawaiian basalt (Turcotte and Oxburgh, 1978). This objection might not apply if mantle plumes are a source of heat for melting of the lower lithosphere or the uppermost asthenosphere rather than a direct source of magma.

An alternative to thermal plumes, proposed by Anderson (1975), is that the plumes are relict compositional conduits. According to Anderson's hypothesis, the Earth accreted inhomogeneously and in the sequence in which compounds would condense from a cooling nebula. Thus, the primitive deep mantle was a material enriched in Ca, Al, Ti, and the refractory trace elements, including U and Th. This material, being less dense than the overlying layers, rose as chemical plumes through buoyancy early in Earth's history and partially melted to yield anorthosites. Present-day hot spots occur above the mantle residua of this partial melting. These plumes provide heat to the base of the lithosphere because they are enriched in heat-producing elements, principally U and Th, and so constitute what could be called radioactive hot spots. Chemical plumes might explain both asthenospheric bumps and also the episodic nature of volcanism. Anderson proposed that the rapid withdrawal of heat by magma could periodically outstrip heat production and therefore temporarily halt magma generation. However, one would think that the chemical inhomogeneities should be seismically detectable.

Richter (1973) and Richter and Parsons (1975) have suggested that the Hawaiian-Emperor Chain and other linear chains might be a consequence of the nonlinear interaction of two different scales of mantle convection, one involving sea-floor spreading and the return flow necessary to conserve mass, and the other a Rayleigh-Benard convection reaching to depths of about 650 km. This latter convection forms rolls whose axes initially are aligned perpendicular to the spreading direction. In time, however, the latitudinal rolls give way to longitudinal rolls with axes parallel to the direction of plate motion (fig. 1.17). The time for the transition to occur depends on the spreading velocity, but may be as short as about 20 m.y. for a fast (about 10 cm/yr) plate like the Pacific plate. Longitudinal rolls will generate alternating bands of tension and compression in the overlying plate. Linear volcanic chains might form along the zones of tension and, either because of modulation of convection amplitude along the roll or because of the fracture properties of the plate, could propagate opposite to the direction of spreading. A feature of this mechanism is that ages out of order can occur. In addition, an age gap of some tens of millions of years could occur near the bend in the Hawaiian-Emperor Chain because of the time required for a new set of longitudinal rolls to be established

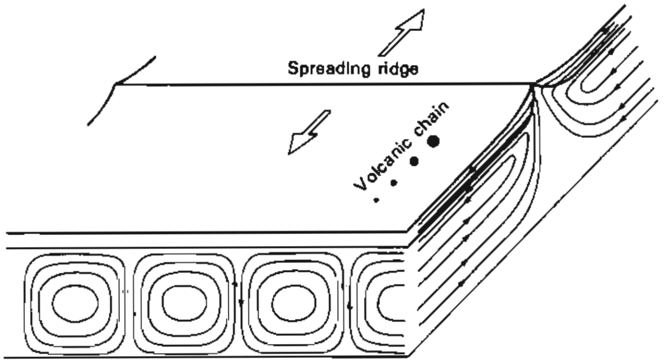

FIGURE 1.17.—Schematic diagram of large-scale asthenospheric flow related to sea-floor spreading and superimposed small-scale longitudinal rolls. Volcanic chain might occur in zone of tension between diverging rolls and would propagate opposite to direction of spreading. From Richter and Parsons (1975).

following a change in spreading direction. The age data for the Hawaiian-Emperor Chain (fig. 1.5), however, show that the propagation is continuous around the bend, although seamounts are sparse on the westernmost Hawaiian Ridge. Another feature of the longitudinal roll model is that parallel volcanic chains should be spaced at some multiple of twice the depth of the convecting layer, which is in accord with the geometry of the major Pacific chains for a convecting depth of about 600 km (Richter, 1973).

SHEAR-MELTING HYPOTHESES

Shear melting with thermal feedback to regulate the propagation rate was proposed by Shaw (1973) to explain the nonlinear time-distance-volume relations along the Hawaiian Chain noted by Jackson and others (1972) and Swanson (1972) (fig. 1.18). According to his hypothesis, the hot spot is the result of a delicately balanced thermomechanical process that derives energy from plate motion and is regulated by a feedback process inherent in the physical properties of the rocks involved. In principle, the idea is quite simple and is based on the observation that a viscous medium will rise in temperature when sheared. Shear occurs within a finite zone between the lower lithosphere and the upper asthenosphere because of their relative motion. As shear proceeds the temperature rises and the viscosity decreases within the shear zone. This allows an increase in the rate of shearing, which in turn produces a further increase in temperature. The increasing temperature eventually results in partial melting and the formation of magma, which rises to the surface to form the volcanoes. The magma carries off excess heat, the temperature decreases rapidly, viscosity increases, and melting stops temporarily as a new cycle is initiated. Each cycle lasts a few million years and is characterized by accelerating propagation of volcanism and eruption volume followed by a sudden halt.

A means of localizing shear melting and fixing the resulting hot spot relative to the mantle was advanced by Shaw and Jackson (1973). They proposed that once partial melting began the residua sinks, forming a type of gravitational anchor that reaches down into the mantle, perhaps to the core-mantle boundary (fig. 1.19). The downwelling anchor not only forms a geographic pinning point for the hot spot but also results in the inflow of fresh mantle material beneath the hot spot, which thus is not limited by supply. There is strong evidence, however, that the depleted residua from partial melting of the most likely parent rocks are less dense than the parent material and would not sink (see, for example, O'Hara, 1975; Boyd and McCallister, 1976; Jordan, 1979). Thus, unless the source of Hawaiian basalt is something quite unusual, the formation of a gravitational anchor seems unlikely, and the shear-melting hypothesis suffers from the lack of both a starting mechanism and a means of localization.

HEAT-INJECTION HYPOTHESIS

It has long been known that the Hawaiian hot spot, among others, is associated with a broad topographic anomaly on the ocean floor, the Hawaiian swell, which has been attributed to some sort of thermal anomaly for more than three decades (see, for example, Dietz and Menard, 1953; Menard, 1955). Only recently, however, has it become clear that the swell may be the result of thermal resetting and thinning of the aging and thickening lithosphere. Detrick and Crough (1978) observed that long-term rates of subsidence of volcanoes in the Pacific are higher than can be accounted for by the subsidence that accompanies the cooling and thickening of the lithosphere as it moves away from the spreading ridge (Parsons and Sclater, 1977; Schroeder, 1984). They proposed that the excess subsidence is the result of thermal resetting of the lithosphere as the aging plate rides over the hot spot. The resetting is accompanied by lithospheric thinning and a rise in the elevation of the sea floor. The rapid subsequent subsidence then represents a gradual return of these shallow areas to normal depths, that is, depths commensurate with the age of the sea floor (see also Crough, 1979, 1983; Epp, 1984). The hypothesis of thermal resetting is supported by anomalously high heat flow along the

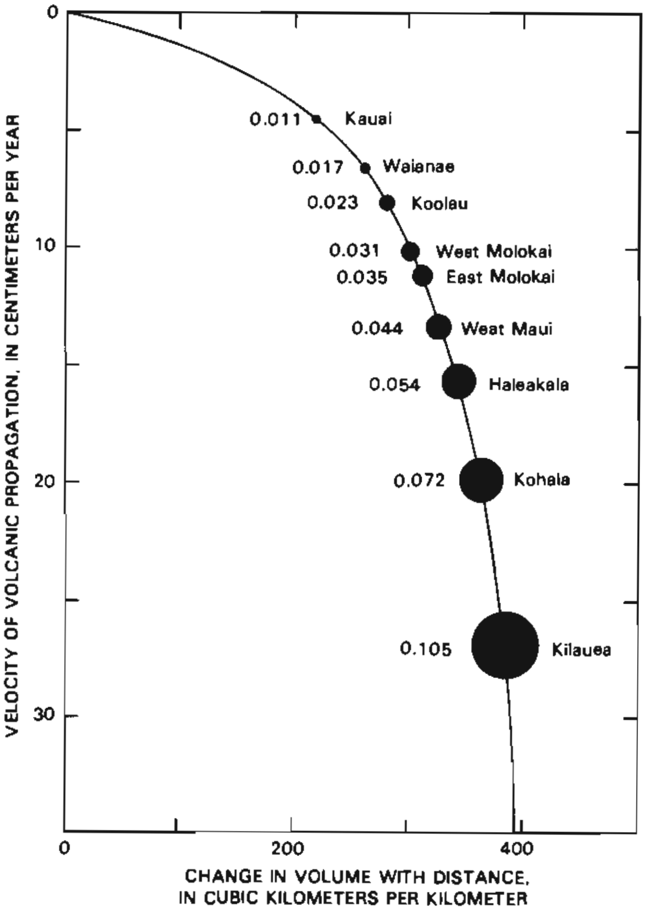

FIGURE 1.18.—Change in volume of lava with respect to unit distance versus change in distance with respect to time (velocity of volcanic propagation) for principal Hawaiian Islands. Diameter of circles approximately proportional to apparent eruption rates, which are also given (in cubic kilometers per year) next to circles. From Shaw (1973).

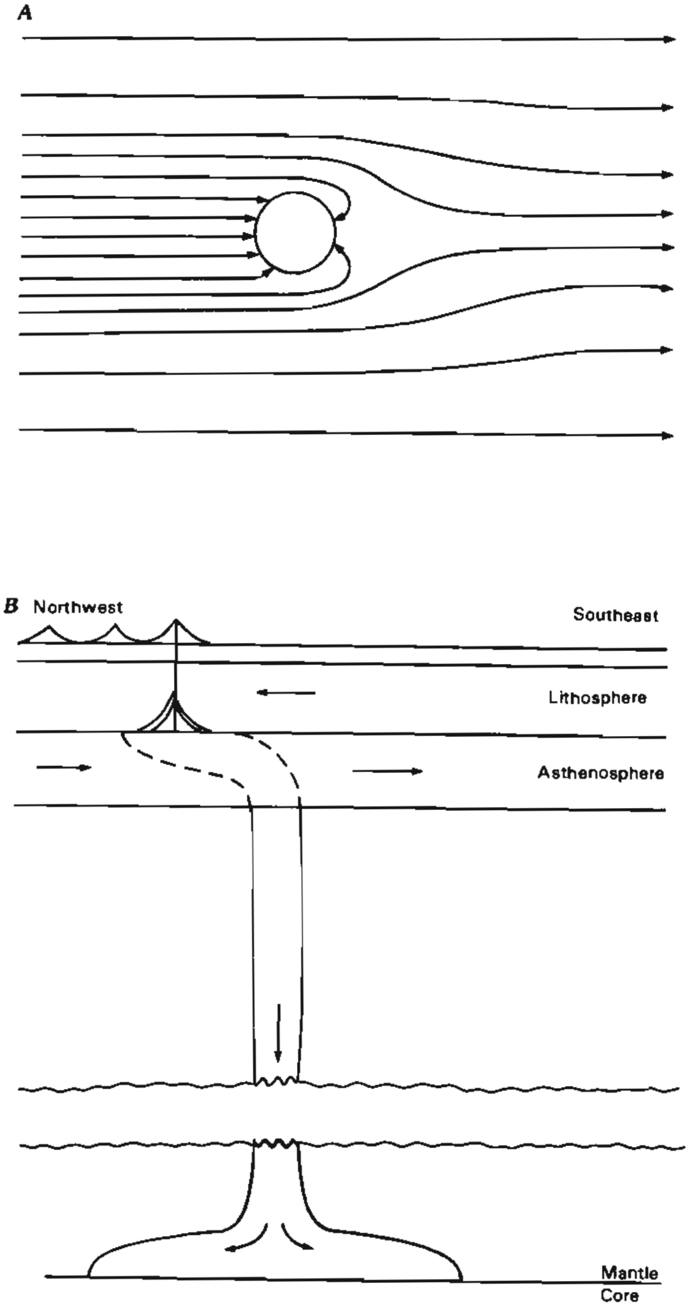

FIGURE 1.19.—Schematic views of possible downwelling of dense residua from tholeiitic melting. *A*, Plan view showing hypothetical flow lines in asthenosphere along horizontal plane taken at time near culmination of melting episode. *B*, Vertical section showing proposed gravitational anchor. From Shaw and Jackson (1973).

Hawaiian Ridge (Detrick and others, 1981). The concept of lithospheric thinning over hot spots is substantiated by the flexural data, which indicate that the lithosphere over hot spots is much thinner than that of comparable age flexed at subduction zones (McNutt, 1984).

Detrick and Crough (1978) recognized that the major problem with their thermal model for the Hawaiian swell is that it requires extremely rapid heating of the lithosphere; a heat flux more than 40 times normal is indicated, if the heating is entirely by conduction. This is because the kinematics of plate motion relative to the hot spot requires the swell to rise in only a few million years, whereas it would take about 100 m.y. at twice the normal heat flux to raise the swell. This problem, however, may not be as serious as it once seemed. More recent modeling by Nakiboglu and Lambeck (1985) demonstrates the sensitivity of these calculations to the lower boundary condition. They argue that most of the Hawaiian swell can be produced by thermal conduction, but a small dynamic component may also be required to support the swell. Another potential solution to this problem, proposed by McNutt (1984), is lithospheric delamination, a process invoked by Bird (1979) to explain volcanism in continental interiors. According to this hypothesis, a strip of the lower lithosphere separates from the upper lithosphere and descends into the asthenosphere. This produces the sudden rise in temperature at the base of the remaining lithosphere required to produce the swell without invoking an unreasonable heat flux. The lateral resistance of the descending strip might also provide the necessary stability of the hot spot with respect to the mantle. It is unclear how delamination might begin, but once started theory suggests that it can propagate at plate velocities (Bird and Baumgardner, 1981).

One problem with delamination is that it requires the sinking into the asthenosphere of the lower lithosphere, which is thought to be one component of the source of ocean-island basalt. For Hawaii the proposed depth of delamination, that is, the thickness of the lithosphere over the hot spot, is slightly less than 30 km (McNutt, 1984), a depth considered to be well above the source region of Hawaiian basalt. It is also clear from pressure-temperature relations that the descending slab would not melt (and if it did the residua would rise rather than sink). Therefore, Hawaiian basalt would have to be generated from the material of the upper asthenosphere, although at lower lithosphere depths, and the lithosphere-asthenosphere boundary would be a purely mechanical one (that is, with no compositional differences across the boundary).

In summary, geophysical models for the Hawaiian hot spot tend to be highly generalized and difficult if not impossible to test. None has yet been advanced that satisfactorily explains all of the geometric, kinematic, physical, and chemical observations from the Hawaiian-Emperor Chain. Although many intriguing and clever ideas have been advanced, the hot-spot mechanism is still somewhat mysterious. Detrick and Crough's (1978) idea that the Hawaiian swell is caused by thermal resetting of the aging ocean crust implies that hot spots are indeed hot. In addition, the possibility that the swell is dynamically supported (Detrick and Crough, 1978) implies that material wells up beneath the lithosphere. Petrologic studies indicate that Hawaiian lava is generated from mantle sources consisting of at least 3 geochemical components; one of these is a primitive undegassed component. The cause of the Hawaiian hot spot is still unknown, but present hypotheses are consistent with Morgan's plume hypothesis in which hot primitive mantle material ascends beneath the ocean lithosphere below Hawaii and reacts with the lithosphere to produce the compositional range of Hawaiian lava.

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APPENDIX 1.1

NOTES ON THE GEOLOGY AND GEOCHRONOLOGY OF INDIVIDUAL VOLCANOES IN THE HAWAIIAN-EMPEROR CHAIN

Following are brief descriptions and comments on the geology and geochronology of all volcanoes in the Hawaiian-Emperor Chain that have been mapped or sampled. References to sources of data are included in the reference list of the main text of the paper. The radiometric ages are conventional K-Ar age determinations unless otherwise indicated; errors are the estimated standard deviations of precision. Volcanoes are discussed from southeast to northwest, that is, from youngest to oldest, using the numbering system (in parentheses) of Bargar and Jackson (1974). Stratigraphic nomenclature used here is from Langenheim and Clague (chapter 1, part II).

Loihi Seamount (no number).—Loihi Seamount is inferred to be the youngest Hawaiian volcano on the basis of its location and seismic activity, the presence of fresh glassy pillow lava, and the occurrence of hydrothermal discharge into the water column. Loihi is located on the southeast flank of Kilauea on the Island of Hawaii and is 30 km offshore and 60 km south-southeast from the summit of Mauna Loa. The seamount rises to 950 m below sea level and has a distinct north-south orientation, delineating two rift zones that extend from the roughly 2.8-km by 3.7-km summit caldera (Malahoff and others, 1982). The volcano is active seismically; persistent swarms of shallow earthquakes that are probably caused by volcanic intrusion or submarine eruptions (Klein, 1982) occur periodically near the summit (Klein and Koyanagi, 1979). Moore and others (1982) describe fresh glassy pillow lava recovered from Loihi Seamount that includes basanite, alkalic basalt, basalt transitional between alkalic and tholeiitic basalt, and tholeiitic basalt. They also demonstrated that the alkalic lava is generally older than the tholeiitic lava and suggested that Loihi Seamount, and presumably all Hawaiian volcanoes, have a stage of alkalic volcanism before the tholeiitic shield stage that is characterized by infrequent, small-volume eruptions of alkalic lava. Further evidence that Loihi Seamount is an active volcano is provided by the discovery of a plume of hydrothermal methane and helium in the water column above Loihi (Horibe and others, 1983; Kim and Craig, 1983) and the presence of water-temperature anomalies recorded by the ANGUS camera sled (Malahoff and others, 1982).

Kilauea Volcano (1).—The lava of Kilauea, currently active and historically the most active volcano in Hawaii, can be divided into the older Hilina Basalt and the younger Puna Basalt, which are separated by the Pahala Ash. The exposed lava consists of tholeiitic basalt and picritic tholeiitic basalt that issued from the 3-km by 5-km summit caldera and the two rift zones. The rift zones extend to the east and the southwest, with the east rift zone extending nearly 50 km from the summit caldera to Cape Kumikahi at the northeast corner of the island and for at least an additional 90 km beneath the sea.

Mauna Loa Volcano (2).—The lava of Mauna Loa is divided into the Ninole Basalt (oldest), the Kahuku Basalt, and the Kau Basalt (youngest). The Kahuku and Kau are separated by the Pahala Ash and are thought to be coeval with the Hilina Basalt and Puna Basalt, respectively, of Kilauea. The exposed lava is all tholeiitic basalt and picritic tholeiitic basalt that issued from the 2.5-km by 4-km summit caldera, named Mokuaweoweo, and two rift zones. The rift zones extend southwest and east-northeast. The southeastern and the southwestern slopes of Mauna Loa are steepened by downfaulting along the Kaoiki and Kealakakua fault systems. Mauna Loa last erupted in 1984. Possible remnants of two earlier shield volcanoes are exposed in the Ninole Hills (Ninole Basalt) and in the vicinity of Kulani. Neither of these earlier shield volcanoes is well delineated and both may be merely deeper parts of the Mauna Loa shield uplifted along normal faults in a manner analogous to that in the Hilina fault system near Puu Kapukapu. With the exception of numerous ^{14}C ages, the sole published age data for Mauna Loa were obtained by Evernden and others (1964) on two samples from the Ninole Basalt. One sample contained negligible radiogenic ^{40}Ar. The other sample had a radiogenic ^{40}Ar content of 2.5 percent and a calculated age of 0.54 Ma. No uncertainty was given for the age, but from the quality of the data we estimate a standard deviation of approximately 0.4 m.y. It seems unlikely that the Ninole Basalt is more than a few hundred thousand years old.

Mauna Kea Volcano (3).—Mauna Kea Volcano last erupted some 3,600 years ago (Porter and others, 1977). The volcano has a well exposed section of shield lava capped by postshield alkalic lava. The rocks are divided into the older Hamakua Volcanics and the younger Laupahoehoe Volcanics. The Hamakua Volcanics consists of shield-stage tholeiitic basalt, olivine tholeiitic basalt, and picritic tholeiitic basalt, and overlying postshield-stage alkalic basalt, ankaramite, and hawaiite. There is no clear boundary between the shield and postshield lavas; tholeiitic and alkalic lavas are intercalated near the boundary (Frey and others, 1984). Most of the surface of Mauna Kea is blanketed by the younger Laupahoehoe Volcanics which is mostly hawaiite, with much less ankaramite and alkalic basalt (West and Garcia, 1982). The Hamakua Volcanics is exposed only in deep erosional canyons.

The rift zones of Mauna Kea are not well defined, but cinder cones are roughly aligned in westerly and southerly directions from the summit. A nearly buried east rift zone is still clearly delineated by a submarine ridge extending nearly 40 km to sea. It is uncertain if a summit caldera existed, but the crude arcuate alignment of some cinder cones, coupled with a large gravity high just south of the summit, indicate that a former caldera may be buried beneath the Laupahoehoe Volcanics.

Porter and others (1977) obtained K-Ar ages on three samples from the Hamakua Volcanics. The two younger flows gave ages of 0.27±0.04 Ma, whereas the older flow gave an age of 0.375±0.050 Ma. K-Ar and ^{14}C ages for flows from the Laupahoehoe Volcanics range from about 0.19 Ma to 4.5 ka. Funkhouser and others (1968) reported a K-Ar age of 0.6±0.3 Ma for a single sample of hawaiite from the Laupahoehoe Volcanics.

Hualalai Volcano (4).—Hualalai Volcano was last active in 1800-01 when two major and several smaller flows issued from a series of vents on the northwest rift zone. With the exception of a large trachyte cone and flow at Puu Waawaa (Waawaa Trachyte Member), the entire subaerial surface of the volcano consists of alkalic basalt flows of the alkalic postshield stage. All subaerial rocks of Hualalai are called the Hualalai Volcanics. A detailed study of the volcano (Moore and others, chapter 20) shows that nearly all the lava is alkalic basalt, with only a few flows that are gradational to hawaiite. Some ^{14}C ages of charcoal from beneath many of these flows demonstrate the youth of the alkalic basalt surface. The structure of the volcano is poorly known, although the northwest and south rift zones are well defined. It is unknown if a summit caldera existed in the past. Recent studies on the submarine northwest rift zone recovered tholeiitic basalt and picritic tholeiitic basalt (Clague, 1982), indicating that Hualalai, like all other Hawaiian volcanoes, had a tholeiitic shield stage. The submarine portion of the rift is overlain by terrace deposits that are inferred to be as old as 120 ka (Moore and Fornari, 1984), which indicates that the tholeiitic shield stage had ended by this time.

Funkhouser and others (1968) reported an age of 0.4±0.3 Ma for the Waawaa Trachyte Member of the Hualalai Volcanics; recent K-Ar results indicate the trachyte is about 105 ka (G.B. Dalrymple, unpub. data, 1985).

Kohala Volcano (5).—Kohala Volcano is composed of the older Pololu Basalt and the younger Hawi Volcanics. The Pololu Basalt is a succession of thin flows of tholeiitic basalt, olivine tholeiitic basalt, and picritic tholeiitic basalt except near the top of the section, where alkalic basalt occurs. Most of the Pololu Basalt represents the shield stage, whereas the uppermost, alkalic part represents the alkalic postshield stage. The younger Hawi Volcanics formed during the alkalic postshield stage and is separated from the Pololu Basalt by an erosional unconformity. Most of the Hawi lava is mugearite, but benmoreite and hawaiite are also present. Cinder cones of the Hawi Volcanics align along two rift zones trending northwest and southeast. Arcuate faults near the summit indicate that a caldera probably formed during eruption of Pololu lava, but Hawi lava has entirely buried it. A gravity high located southeast of the summit may correspond to the approximate location of this inferred caldera. Hawi lava is absent from an 11-km section on the northwest side of the volcano. Flows are deflected from this zone by a series of fault scarps in the summit region that bounds a northwest-trending graben 10 km long and 2–5 km wide. Lava erupted inside the graben, filled it, flowed to the northwest and southeast ends, and overflowed most of the southwest rim. Feigenson and others (1983) made a detailed petrologic study of stratigraphically controlled lava samples from the Pololu Volcanics, and Lanphere and Frey (1985) made a similar study of samples from the Pololu Basalt and Hawi Volcanics.

Evernden and others (1964) obtained an age of 0.43 Ma for one sample of tholeiitic basalt from the Pololu Basalt. Dalrymple (1971) obtained scattered age results that averaged 0.7±0.15 Ma on five samples from the Pololu Basalt. The best data for lava of the Pololu is from McDougall and Swanson (1972), who dated nine flows ranging in age from 0.459±0.028 to 0.304±0.091 Ma. The average of the three oldest flows is 0.43±0.02 Ma. Ages on 12 samples from the Hawi Volcanics (McDougall, 1969; McDougall and Swanson, 1972) range from 0.261±0.005 to 0.061±0.001 Ma.

East Maui Volcano (6).—East Maui Volcano is the youngest volcano in the Hawaiian Islands having rejuvenated-stage volcanics. The volcano was last active in about 1790 (Oostdam, 1965). The oldest unit is the Honomanu Basalt, a series of tholeiitic basalt, olivine tholeiitic basalt, and picritic tholeiitic basalt flows that represents the shield stage. Above sea level these flows are nearly completely buried by those of the overlying Kula Volcanics and Hana Volcanics. The Kula Volcanics is composed predominantly of hawaiite with some ankaramite and alkalic basalt and represents the alkalic postshield stage. There is little evidence of extensive erosion between the shield and postshield lavas. The Hana Volcanics is composed mostly of the same rock types as the Kula Volcanics, but it erupted after an erosional period; it represents an alkalic rejuvenated stage of volcanism. Three rift zones are delineated by the location of vents for the Kula and Hana Volcanics. The east and southwest rifts are characterized by vents of both these units, whereas the north rift has only Kula Volcanics vents. The Hana Volcanics is unique among Hawaiian rejuvenated stage volcanic rocks in that its vents are aligned along the preexisting rift zones, the duration of the erosional period is rather short (<0.4 m.y.), and ankaramite and hawaiite are present. Chen and Frey (1983, 1985) present a detailed geochemical study of lava from all three eruptive stages.

Naughton and others (1980) reported ages for 7 samples of the Honomanu Basalt from three localities. The individual sample ages range from 0.54 to 0.91 Ma. Probably the best age for the Honomanu Basalt is the mean of 0.75±0.04 Ma of the four measurements on samples from the so-called crater of Haleakala. McDougall (1964) dated two samples of the Kula Volcanics at 0.46 and 0.86 Ma, whereas the mean of four samples from the Kula Volcanics dated by Naughton and others (1980) is 0.41±0.09 Ma. No ages have been determined for the Hana Volcanics.

Kahoolawe (7).—The volcanic rocks of Kahoolawe have not been subdivided. The only formation, the Kanapou Volcanics, includes tholeiitic basalt and olivine tholeiitic basalt of the shield stage, tholeiitic and alkalic basalt of the caldera-filling phase, and alkalic basalt and hawaiite of the alkalic postshield stage. Five vents along the seacliff in Kanapou Bay erupted alkalic basalt following an extended period of volcanic quiescence; these vents presumably represent an alkalic rejuvenated stage. The volcano was built by eruptions along a prominent west-southwest rift zone and two less pronounced rifts trending east and north. Most of the vents have been removed by erosion, but remnants of about six vents remain. The caldera of 5 km diameter lies at the eastern end of the island and has been breached by the sea.

Naughton and others (1980) dated two samples collected by H.S. Palmer in 1925 from the upper (alkalic) part of the Kanapou Volcanics. The mean of the two measurements is 1.03±0.18 Ma.

West Maui Volcano (8).—The volcanic rocks of West Maui are divided into the Wailuku Basalt, Honolua Volcanics, and Lahaina Volcanics. The Wailuku Basalt consists of tholeiitic basalt, olivine tholeiitic basalt, and picritic tholeiitic basalt of the shield stage and of alkalic basalt of a caldera-filling phase. The Honolua Volcanics, which represents an alkalic postshield stage, consists of a thin discontinuous cap of mugearite with some trachyte and hawaiite. The Lahaina Volcanics followed a long period of erosion and consists of the cones and flows of four small eruptions of basanite and olivine-rich basanite. The Lahaina Volcanics represents the alkalic rejuvenated stage. The volcano has ill-defined rift zones delineated by dike swarms trending northeast and south and by vents of the Honolua Volcanics trending north and south from the small central caldera. The caldera-filling lava is severely altered by late gases; erosion has preferentially removed these altered rocks in Iao Valley.

McDougall (1964) dated three samples of the Wailuku Basalt, and the ages all fall within the narrow range of 1.30–1.33 Ma with a mean of 1.32±0.04 Ma. Naughton and others (1980) obtained ages of 1.58 and 1.97 Ma on two samples from the Wailuku, but the precision of the measurements is poor. The samples dated by Naughton and his colleagues may be from an older part of the shield than those dated by McDougall (Naughton and others, 1980). McDougall's results for four samples of the Honolua Volcanics range only from 1.18 to 1.20 Ma, whereas Naughton and others (1980) measured an age of 1.50±0.13 Ma for a single sample of the Honolua Volcanics. Naughton and others (1980) dated one sample from the Lahaina Volcanics at 1.30±0.10 Ma, an age which appears to be too old on stratigraphic grounds.

Lanai (9).—Only tholeiitic lava was erupted during the shield stage and caldera-collapse phase of Lanai Volcano; no later alkalic lava is known. The Lanai Basalt consists of tholeiitic basalt, olivine tholeiitic basalt, and picritic tholeiitic basalt that erupted from the northwest, southwest, and southeast rift zones and from the summit caldera underlying the present-day Palawai Basin. An extensive dike swarm marking the southwest rift crops out along the Kaholo Pali. Most of the dikes are nearly vertical and are about 30 cm thick.

Bonhommet and others (1977) measured ages for six samples of the Lanai Basalt that were collected on the southern part of the Lanai shield. The data fit a K-Ar isochron indicating an age for the Lanai Basalt of 1.28±0.04 Ma. Naughton and others (1980) obtained ages of 0.71±1.27 to 0.86±0.55 Ma for three samples from the northeastern part of the island. They speculate that the northeastern part of the shield may be somewhat younger than the southern part, but the mean of their three ages (0.81±0.66 Ma) is not significantly different from the more precise isochron age of Bonhommet and others (1977) at the 95-percent level of confidence.

East Molokai Volcano (10).—The lava of East Molokai is subdivided informally into an upper and a lower member of the East Molokai Volcanics. The lower member consists of tholeiitic basalt, olivine tholeiitic basalt, and picritic tholeiitic basalt characteristic of the shield stage, but alkalic basalt of the postshield stage occurs in the upper part of the lower member. Beeson (1976) and Clague and Beeson (1980) have shown that tholeiitic and alkalic basalt are intercalated in the upper part of the lower unit. The upper member consists predominantly of mugearite, with smaller amounts of hawaiite and trachyte and represents the alkalic postshield stage. Following an extended erosional period, during which the 1,200-m cliffs on the north side of the island formed, alkalic basalt and basanite of the rejuvenated stage Kalaupapa Volcanics erupted to form the Kalaupapa Peninsula and Mokuhooniki Island, a tuff cone located offshore of the east end of the island. East Molokai Volcano was built by eruptions along eastward- and west-northwestward-extending rift zones and from a summit caldera about 2.5 km by 7 km in size. The caldera-filling lava flows are similar to those of the lower member except that they are horizontal, more massive, and more extensively altered.

McDougall (1964) dated two samples from the lower member of the East Molokai Volcanics. Both ages agree at 1.52 Ma. Naughton and others (1980) obtained an age of 1.76 ± 0.07 Ma based on several analyses of a single sample. McDougall also dated three samples of the upper member and obtained ages of 1.35 to 1.49 Ma. A basalt sample from the Kalaupapa Peninsula was dated at 1.24 ± 0.16 Ma by Naughton and others (1980), but this appears to be too old in view of the younger ages (0.35 ± 0.03 to 0.57 ± 0.02) obtained for three samples of the Kalaupapa Volcanics by Clague and others (1982).

West Molokai Volcano (11).—The volcanic rocks of West Molokai belong to the West Molokai Volcanics. Most of the exposed lava is tholeiitic basalt of the shield stage. This lava erupted from an east-northeast rift zone that crosses the summit area. A less pronounced rift trends toward the northwest. There is no evidence of a summit caldera. Alkalic lava of the postshield stage, predominately hawaiite with subordinate alkalic basalt, erupted from a series of cinder and spatter cones located mainly on the northwest rift zone. No rejuvenated-stage lava is known. A shoal area extends beneath the sea to the west-southwest nearly 65 km and includes Penguin Bank. This bank probably represents a separate volcanic center, but it has not been studied and little is known of its history.

McDougall (1964) dated one sample from the summit of the West Molokai shield at 1.89 Ma. From the sample locality, we conclude that it is from the tholeiitic shield (lower part of West Molokai Volcanics). Naughton and others (1980) dated six samples of the lower part of the West Molokai Volcanics from three localities. The three localities gave mean ages of 1.84 ± 0.07, 1.90 ± 0.06, and 1.52 ± 0.06 Ma.

Koolau Volcano (12).—Koolau Volcano on Oahu is composed of tholeiitic basalt, olivine tholeiitic basalt, and rather rare picritic tholeiitic basalt that erupted from a long rift system oriented northwest-southeast. These shield-building flows make up the Koolau Basalt. Lava that ponded in the 16-km by 13-km caldera is also tholeiitic and is called the Kailua Member of Koolau Basalt. The rift zones are identified by an extensive dike complex consisting of hundreds of nearly vertical dikes that average 60–90 cm thick. A few of the youngest flows of the Koolau Basalt appear to be transitional between tholeiitic and alkalic basalt. The rejuvenated-stage Honolulu Volcanics erupted from about 36 groups of vents following a long period of volcanic quiescence and erosion. The lava is strongly alkalic and ranges in composition from alkalic basalt, basanite, and nephelinite, to melilitite. The vents from which these rocks erupted show no relationship to the preexisting rift zones or caldera-bounding faults. Many of the vents formed by violent hydromagmatic eruptions that formed tuff cones commonly containing accidental blocks of Koolau Basalt and coral limestone. Clague and Frey (1982) presented a detailed trace-element geochemical study of the lava and summarized the geology of the Honolulu Volcanics.

K-Ar ages have been reported for a large number of samples from the Koolau Basalt by McDougall (1964), Funkhouser and others (1968), McDougall and Ur-Rahman (1972), and Doell and Dalrymple (1973), who also summarized and evaluated the ages. The best ages for the Koolau Basalt range from 1.8 to 2.7 Ma. Ages for lava of the rejuvenated-stage Honolulu Volcanics range from about 0.03 to 0.9 Ma (Funkhouser and others, 1968; Gramlich and others, 1971; Stearns and Dalrymple, 1978; Lanphere and Dalrymple, 1980).

Waianae Volcano (13).—Waianae Volcano is divided into the older Waianae Volcanics and the younger Kolekole Volcanics. The Waianae Volcanics is subdivided into the Lualualei, Kamaileunu, and Palehua Members. The Lualualei Member consists of tholeiitic basalt, olivine tholeiitic basalt, and picritic tholeiitic basalt of the shield stage. The Kamaileunu Member consists of rocks that accumulated inside the 14-km-wide caldera and is also composed mostly of tholeiitic lava, although alkalic rocks are present near the top. The Kamaileunu Member also includes the only occurrence of icelandite and rhyodacite (Mauna Kuwale Rhyodacite Flow) in the Hawaiian Islands. The Palehua Member consists mainly of hawaiite with rather rare alkalic basalt flows; it represents the alkalic postshield stage. The Kolekole Volcanics represents the group of young cones near the southwest end of the island and a single flow of alkalic lava erupted in Kolekole Pass. The tholeiitic shield lava erupted from three rift zones trending northwest, south-southeast, and northeast. There is no unconformity between tholeiitic and alkalic lava within the caldera; the boundary is transitional and may be similar to the one on East Molokai. K-Ar ages have been determined for a large number of samples from the Waianae Volcanics by McDougall (1964), Funkhouser and others (1968), McDougall and Ur-Rahman (1972), and Doell and Dalrymple (1973), who also summarized and evaluated all of the data. Ages from the Lualualei and Kamaileunu Members range from about 3.0 to 3.9 Ma. Ages from the Palehua Member range from about 2.5 to 3.2 Ma.

Kauai (14).—The Island of Kauai consists of a single large shield volcano with a summit caldera 16–19 km across. The Waimea Canyon Basalt has been divided into four members, but all consist of tholeiitic basalt, olivine tholeiitic basalt, and abundant picritic tholeiitic basalt. The Napali Member represents the shield stage, whereas the Olokele and Makaweli Members represent the caldera-filling phase, having filled the summit caldera and a 6-km-wide graben on the south flank, respectively. Two other calderas formed on the flanks of the Kauai shield volcano: the Lihue depression, 11–16 km across, was apparently not filled by tholeiitic lava; the Haupu caldera, roughly 3 km across was filled with thick ponded flows called the Haupu Member of the Waimea Canyon Basalt. These are the only flank calderas known in the Hawaiian Islands. Near the top of the Olokele and Makaweli Members, a single flow of hawaiite rests on a soil 30–60 cm thick. This single flow apparently represents the alkalic postshield stage on Kauai. Unlike most Hawaiian volcanoes, Kauai has no well-defined rift zones; dikes radiate from the summit caldera in all directions, although they are more concentrated in the northeast and west-southwest directions.

Following a long period of volcanic quiescence and deep erosion, the alkalic rejuvenated stage Koloa Volcanics erupted from at least 40 vents concentrated on the south and east flanks of the shield. The lava ranges from alkalic basalt, basanite, and nephelinite, to melilitite. The abundant vents located along the southeast coast erupted almost entirely alkalic basalt.

McDougall (1964) reported ages for three samples from the Napali Member ranging from 3.63 to 5.77 Ma. Evernden and others (1964) obtained an age of 3.43 Ma for a single sample from the Napali. In a more recent study, McDougall (1979) reported K-Ar ages ranging from 3.81 ± 0.06 to 5.14 ± 0.20 Ma for 16 samples of the Napali collected from three localities. He concluded that some of the variation was probably due to differential Ar loss, that the Napali Member was erupted between about 5.1 and 4.3 Ma, and that the Napali lava in Waipio Valley was erupted over a short time interval at about 5.1 ± 0.2 Ma.

Ages of 4 samples from the Makaweli Member range from 3.60 to 4.15 Ma (McDougall, 1964). Only three samples from the Koloa Volcanics (rejuvenated stage) have been dated; two samples have ages of 0.62 and 1.21 Ma (Evernden and others, 1964) and another an age of 1.46 Ma (McDougall, 1964).

Niihau (15).—The Island of Niihau consists of a deeply eroded shield volcano mantled by lava of the alkalic rejuvenated stage on the north, west, and south sides. The Paniau Basalt consists of tholeiitic basalt and olivine tholeiitic basalt of the shield stage and the remnants of a single alkalic postshield stage vent at Kaeo. Several dikes exposed near the eastern coastline are also of alkalic basalt and presumably fed vents that have been completely removed by erosion. A magnificent dike swarm is exposed in the eastern seacliff (Dalrymple and others, 1973, fig. 5); these dikes trend southwest and represent a rift zone. The summit of the volcano was northeast of the present-day island, and the eastern side of the volcano has been removed by erosion or downfaulting. The period of volcanic quiescence and marine erosion that removed the eastern side of the shield was followed by eruption of the alkalic rejuvenated-stage lava of the Kiekie Basalt, which is entirely alkalic basalt. Lehua Island off the north shore is a breached tuff cone of the Kiekie Basalt.

Ages for Niihau have not been published, but data for 11 tholeiitic flows and dikes of the Paniau Basalt fit a K-Ar isochron with an age of 4.89 ± 0.11 Ma (G.B. Dalrymple, unpub. data, 1983).

Kaula Island (15A).—Kaula Island is a small tuff cone on a large submarine edifice. The edifice almost surely represents a separate shield volcano related to the Hawaiian Islands, but it has not been sampled. The tuff cone is probably a vent of the alkalic rejuvenated stage. Garcia, Frey and Grooms (in press) described accidental blocks of tholeiitic basalt, basanite, phonolite, and ultramafic xenoliths that occur in the tuff.

Garcia, Grooms, and Naughton (in press) obtained K-Ar ages for two phonolite blocks and a basanite from the tuff; they determined ages of 4.00±0.09 and 4.22±0.25 Ma for phonolite samples, 3.98±0.70 Ma for a biotite separated from the phonolite, and 1.8±0.2 Ma for the basanite.

On the basis of the composition and age of the phonolite, we propose that the phonolite is from the alkalic postshield stage, the basanite blocks are from rejuvenated-stage flows underlying the tuff cone (Garcia, Frey, and Grooms, in press), and tholeiitic basalt represents the shield stage.

Nihoa Island (17).—Nihoa Island is a remnant of a large tholeiitic shield with flows dipping 5°–10° to the southwest. All the flows exposed on Nihoa are of tholeiitic basalt, and they range from aphyric to porphyritic in texture (Dalrymple and others, 1974).

Funkhouser and others (1968) obtained an age of 7.5±0.4 Ma for a single sample from Nihoa Island. Dalrymple and others (1974) reported a best weighted mean age of 7.2±0.3 Ma for six samples of tholeiitic basalt from the island.

Unnamed Seamount (19).—A single sample dredged by the Hawaii Institute of Geophysics from this seamount has been analyzed (Garcia, Frey, and Naughton, in press). The samples in dredge 9-11 are moderately altered picritic tholeiitic to transitional basalt with about 30 percent olivine phenocrysts. These probably erupted during the late shield stage or the caldera-filling phase. The seamount is undated.

Unnamed Seamount (20).—On the second leg of the Hawaii Institute of Geophysics cruise 72-07-02, dredge 51 recovered tholeiitic basalt with 20 percent phenocrysts of augite, plagioclase, and olivine, and aphyric alkalic lava of basanite composition (Clague, 1974a; Garcia, Frey, and Naughton, in press). These rocks probably erupted during the shield and the alkalic rejuvenated stages, respectively. Garcia, Frey, and Naughton (in press) obtained a weighted mean age of 9.6±0.8 Ma for four analyses of two of the dredged alkalic basalt samples.

Unnamed Seamount (21).—On the second leg of the Hawaii Institute of Geophysics cruise 72-07-02, dredge 49 recovered tholeiitic to transitional basalt containing 20 percent phenocrysts of olivine and augite (Clague, 1974a). This lava probably erupted during the shield stage. The volcano is undated.

Necker Island (23).—Samples have been collected from Necker Island (Dalrymple and others, 1974), and others have been dredged from the submarine flanks of the volcano during Hawaii Institute of Geophysics cruises 72-07-02 (second leg, dredge 48) and KK84-08-06-01 (Clague, 1974a; Campbell and others, 1984). The subaerial samples are mostly picritic tholeiitic basalt collected from flows dipping 5°–10° to the north-northwest. Palmer (1927) described two dikes that are alkalic lava. One is highly altered, but on the basis of chemical analysis appears to be a nephelinite; the other is described as a hawaiite. These two dikes probably fed vents during the alkalic rejuvenated stage and alkalic postshield stage, respectively. The single lava sample dredged in 1972 is a rhyolite porphyry (Clague and Dalrymple, 1975). This rock type is unknown from elsewhere in the Hawaiian-Emperor Chain, and we suspect that it is either an ice-rafted erratic or a piece of ship's ballast. The 1984 dredges have not yet been analyzed but contain calcareous sediment, volcaniclastic breccia, basalt, and hyaloclastite.

Funkhouser and others (1968) reported an age of 11.3±0.6 Ma for a single sample of subaerial basalt. Dalrymple and others (1974) dated two samples of tholeiitic basalt from the island; they gave a mean age of 10.3±0.4 Ma. The rhyolite porphyry has a Cretaceous age (Clague and Dalrymple, 1975).

La Perouse Pinnacle (French Frigates Shoal) (26).—La Perouse Pinnacle and an even smaller adjacent rock are the only subaerial exposures of volcanic rock within French Frigates Shoal, a coral atoll consisting of 15 or 16 small sand islets. La Perouse Pinnacle is a stack of lava flows that dip 1°–2° to the northwest. The subaerial flows are picritic tholeiitic basalt (Dalrymple and others, 1974) that probably erupted during the shield stage. Four dated samples have a mean age of 12.0±0.4 Ma.

Brooks Bank (28).—Three samples have been analyzed from dredge 41 of the second leg of the Hawaii Institute of Geophysics cruise 72-07-02 (Clague, 1974a; Garcia, Frey, and Naughton, in press). Two of these samples are hawaiite, probably from the same flow, and the third sample is an olivine basalt transitional between tholeiitic and alkalic basalt. The hawaiite probably erupted during the alkalic postshield stage and the transitional basalt during either the late shield stage or the caldera-collapse phase. The hawaiite and alkalic basalt have a mean age of 13.0±0.06 Ma.

St. Rogatien Bank (29).—A single sample has been analyzed from dredge 44 of the second leg of the Hawaii Institute of Geophysics cruise 72-07-02 (Clague, 1974a). The sample is an aphyric hawaiite that probably erupted during the alkalic postshield stage; it has not been dated.

Gardner Pinnacles (30).—The two rocks that constitute Gardner Pinnacles are the westernmost subaerial exposures of volcanic rock in the Hawaiian Chain. The alkalic basalt flows that make up the rocks dip 15° to the west and are cut by several east-trending dikes (Dalrymple and others, 1974). Dredged samples of geochemically similar, though less differentiated, alkalic basalt were recovered in dredge 37 from the second leg of the Hawaii Institute of Geophysics cruise 72-07-02 (Clague, 1974; Garcia, Frey, and Naughton, in press). A later dredge on the flank of Gardner Pinnacles (HIG dredge 6-7; see Garcia, Frey, and Naughton, in press) recovered largely unaltered picritic tholeiitic basalt. We infer that the picritic tholeiitic basalt erupted during the shield stage and the alkalic basalt flows during the postshield stage. Additional samples have recently been recovered during Hawaii Institute of Geophysics cruise KK84-04-28-05 from a number of dredge stations on Gardner Pinnacles, but these have yet to be analyzed (Campbell and others, 1984).

Samples from the island were too altered for dating (Dalrymple and others, 1974), but Garcia, Frey, and Naughton (in press) obtained a weighted mean age of 12.3±1.0 Ma for two dredged samples of alkalic basalt and one of tholeiitic basalt.

Laysan Island (36).—A single dredge during U.S. Geological Survey cruise LEE8-76-NP recovered a variety of hawaiite and mugearite pebbles (Dalrymple and others, 1981) that probably erupted during the alkalic postshield stage. Conventional K-Ar and ^{40}Ar-^{39}Ar measurements on five of the samples fall within the range 18.8–21.4 Ma, and ^{40}Ar-^{39}Ar incremental heating experiments on three samples gave a mean age of 19.9±0.3 Ma.

Northampton Bank (37).—A Hawaii Institute of Geophysics cruise sampled the south side of Northampton Bank and recovered coral-reef debris, picritic tholeiitic basalt, and olivine tholeiitic basalt that probably erupted during the shield stage. Dalrymple and others (1981) reported conventional K-Ar and ^{40}Ar-^{39}Ar age data for three dredged samples of tholeiitic basalt. Only one of the samples gave a ^{40}Ar-^{39}Ar age spectrum plateau. The inferred age for that sample is 26.6±2.7 Ma.

Pioneer Bank (39).—On the second leg of the Hawaii Institute of Geophysics cruise 72-07-02, dredge 25 recovered pillow breccia of olivine tholeiitic basalt (Clague, 1974a) that probably erupted during the shield stage. The volcano is undated.

Pearl and Hermes Reef (50).—On the second leg of the Hawaii Institute of Geophysics cruise 72-07-02, dredge 24 recovered round clasts of alkalic basalt, hawaiite, and nepheline phonolite (Clague and others, 1975) that probably erupted during the alkalic postshield stage. It is possible that the phonolite sample erupted during an alkalic rejuvenated stage, although other phonolite samples from Koko Seamount in the Emperor Seamounts are all interpreted to have erupted during the alkalic postshield stage (Clague, 1974a). The weighted mean age of phonolite, hawaiite, and alkalic basalt is 20.6±0.5 Ma.

Ladd Bank (51).—On the second leg of the Hawaii Institute of Geophysics cruise 72-07-02, dredge 23 recovered a single fresh clast of ankaramite vitrophyre that is compositionally similar to a basanite or nephelinite (Clague, 1974a). This sample probably erupted during an alkalic rejuvenated stage; it is undated.

Midway Island (52).—In 1965, two holes were drilled through the reef on Midway and into flows of tholeiitic basalt (Ladd and others, 1967). Analyses of the tholeiitic flows are presented in Dalrymple and others (1974) and of hawaiite and mugearite cobbles from a conglomerate overlying the flows in Dalrymple and others (1977). We infer that the tholeiitic flows erupted during the shield stage and the hawaiite and mugearite during an alkalic postshield stage.

Dalrymple and others (1974) reported ages for four samples of tholeiitic basalt from the reef drill hole at Midway. The ages ranged from 10.8 to 18.2 Ma. In the later study, Dalrymple and others (1977) reported an age for Midway of 27.7 ± 0.6 Ma based on conventional K-Ar and ^{40}Ar-^{39}Ar analyses of two unaltered samples of hawaiite and mugearite from the conglomerate. Incremental heating experiments showed that the conventional K-Ar ages obtained earlier for the tholeiitic basalt samples do not represent crystallization ages.

Nero Bank (53).—Scripps Institution of Oceanography cruise TASADAY III recovered a vitrophyre of picritic tholeiitic basalt that probably erupted during the shield stage (Clague, 1974a); it is undated.

Unnamed Seamount (57).—On the second leg of the Hawaii Institute of Geophysics cruise 72-07-02, dredge 20 recovered several samples of open-textured alkalic basalt that probably erupted during an alkalic postshield stage (Clague and others, 1975). Three samples of the basalt have concordant K-Ar ages with a mean of 28.0 ± 0.04 Ma.

Unnamed Seamount (58).—DSDP Site 311, located 240 km west of Midway Island, recovered volcanogenic deposits from the archipelagic apron of this volcano (Larson and others, 1975) that yielded a nannoplankton age of 31–28 Ma (Bukry, 1975).

Unnamed Seamount (63).—Scripps Institution of Oceanography cruise TASADAY III recovered a wide range of alkalic lava types including ankaramite, analcime tephrite, amphibole-bearing tephrite, and amphibole-bearing hawaiite (Clague, 1974a, 1974b; Clague and others, 1975). These strongly alkalic rocks probably originated by crystal fractionation from alkalic rejuvenated-stage basanitic parental magma. Clague and others (1975) obtained concordant K-Ar results from three samples of the alkalic lava; the mean age is 27.4 ± 0.05 Ma.

Hancock Seamount (64).—Hawaii Institute of Geophysics cruise KK84-04-28-05 recently recovered samples in a number of dredges from Hancock Seamount; these samples have not been analyzed or dated (Campbell and others, 1984).

Colahan Seamount (65).—On U.S. Geological Survey cruise L8-82-NP, dredge 4 recovered samples of transitional basalt, tephrite, and amphibole-bearing hawaiite (Duncan and Clague, 1984; D.A. Clague, unpub. data, 1983) that probably erupted during an alkalic rejuvenated stage. Analysis of these samples is still in progress; therefore the identification of eruptive stage is less certain than for the other seamounts. Duncan and Clague (1984) have reported ^{40}Ar-^{39}Ar total-fusion ages of 37.5 ± 0.3 and 39.8 ± 0.2 Ma for two alkalic basalt samples.

Abbott Seamount (65A).—On U.S. Geological Survey cruise L8-82-NP, dredges 2 and 3 recovered samples of transitional to alkalic basalt that probably erupted during the late shield stage or caldera-collapse phase (Duncan and Clague, 1984). Analysis of these samples is still in progress. Duncan and Clague (1984) reported ^{40}Ar-^{39}Ar total-fusion ages of 40.4 ± 0.5 and 36.3 ± 0.3 Ma for two of the samples.

Kammu Seamount (66).—On Scripps Institution of Oceanography cruise AIRES VII, dredge 54 recovered abundant carbonate reef debris but no volcanic rocks. N. Sachs (quoted in Clague and Jarrard, 1973) identified *Spiroclypeus variablis* Tan., a large foraminifer of late Eocene age.

Daikakuji Seamount (67).—On Scripps Institution of Oceanography cruise AIRES VII, dredge 55 recovered a range of lava samples including hypersthene-bearing tholeiitic basalt, basalt transitional between tholeiitic and alkalic basalt, and alkalic basalt (Clague, 1974a; Dalrymple and Clague, 1976). Microprobe analyses of glass rinds on some of these samples are in agreement with the published analyses on altered whole-rock samples. The tholeiitic basalt is interpreted to have erupted during the shield stage, the transitional basalt during the late shield stage or caldera-filling phase, and the alkalic basalt during the alkalic postshield stage.

Dalrymple and Clague (1976) made conventional K-Ar and ^{40}Ar-^{39}Ar age determinations on tholeiitic and alkalic basalt and on plagioclase separates. On the basis of ^{40}Ar-^{39}Ar incremental-heating results from the alkalic basalt and ^{40}Ar-^{39}Ar total-fusion analyses of the plagioclases samples, they concluded that the best age for the seamount was 42.4 ± 2.3 Ma.

Yuryaku Seamount (69).—On Scripps Institution of Oceanography cruise AIRES VII, dredge 53 recovered several fairly fresh pebbles of alkalic basalt (Clague, 1974a; Clague and others, 1975; Dalrymple and Clague, 1976). These samples probably erupted during the alkalic postshield stage.

Clague and others (1975) determined an age of 43.4 ± 1.6 Ma for Yuryaku on the basis of ^{40}Ar-^{39}Ar incremental-heating experiments on two dredged samples of alkalic basalt.

Kimmei Seamount (72).—On Scripps Institution of Oceanography cruise AIRES VII, dredges 51 and 52 recovered several samples of alkalic basalt that have been analyzed (Clague, 1974a; Dalrymple and Clague, 1976). Two of these samples are rather severely phosphatized, but all three probably erupted during the alkalic postshield stage.

Dalrymple and Clague concluded that the best age for Kimmei was 39.9 ± 1.2 Ma from ^{40}Ar-^{39}Ar incremental-heating experiments on three dredged samples of alkalic basalt.

Koko Seamount, southeast part (74).—On Scripps Institution of Oceanography cruise AIRES VII, dredge 43 recovered a large collection of rounded volcanic beach cobbles and abundant coral fragments. The volcanic cobbles include tholeiitic basalt, alkalic basalt, hawaiite, mugearite, trachyte, and phonolite (Clague, 1974a). The tholeiitic basalt probably erupted during the shield stage and the entire suite of related alkalic lava types probably erupted during the alkalic postshield stage. DSDP Leg 32 drilled two shallow holes on Koko Seamount, but neither reached volcanic basement (Larson and others, 1975). The structure and seismic stratigraphy of the seamount are described by Davies and others (1972) and Greene and others (1980).

Clague and Dalrymple (1973) obtained conventional K-Ar and ^{40}Ar-^{39}Ar total fusion data on seven dredged samples of sanidine trachyte, alkalic basalt, and phonolite. Krummenacher (cited in Clague and Jarrard, 1973) obtained K-Ar ages of sanidine from two trachyte samples. The data are concordant and have a mean of 48.1 ± 0.8 Ma (Dalrymple and Clague, 1976).

Koko Seamount, northwest flank (76).—On Scripps Institution of Oceanography cruise AIRES VII, dredge 44 recovered pillow fragments of differentiated tholeiitic basalt from the northwest flank of Koko Seamount (Clague and Dalrymple, 1972; Clague 1974a). This lava probably erupted from a rift zone during the shield stage.

Ojin Seamount (81).—DSDP Leg 55 drilled site 430 through a lagoonal sediment pond near the center of Ojin Seamount (Jackson and others, 1980). Five lava flows were penetrated, including four flows of aphyric to sparsely porphyritic hawaiite and an underlying flow of tholeiitic basalt (Kirkpatrick and others, 1980). The overlying sediment consists of shallow-water carbonate reef or bank deposits. The flows were clearly erupted subaerially: a red soil zone was recovered between two of them. The four hawaiite flows were apparently erupted rather rapidly, because their paleomagnetic inclinations are very similar (Kono, 1980). The lowermost tholeiitic flow probably erupted during the shield stage, whereas the hawaiite flows probably erupted during an alkalic postshield stage.

Dalrymple and others (1980) obtained an age of 55.2 ± 0.7 Ma for Ojin on the basis of ^{40}Ar-^{39}Ar incremental-heating results from two samples of hawaiite and one sample of tholeiitic basalt recovered during drilling of DSDP site 430.

Jingu Seamount (83).—A Hawaii Institute of Geophysics cruise in July 1977 recovered several fresh samples and abundant moderately altered samples of hawaiite and mugearite (Dalrymple and Garcia, 1980) that probably erupted during an alkalic postshield stage.

Dalrymple and Garcia (1980) reported an age of 55.4±0.9 Ma for Jingu based on ^{40}Ar-^{39}Ar incremental-heating experiments on three of these dredged samples of hawaiite and mugearite.

Nintoku Seamount (86).—DSDP Leg 55 drilled site 432 into a lagoonal sediment pond on the top of Nintoku Seamount (Jackson and others, 1980). Samples of three lava flows were recovered from beneath sandstone, conglomerate, and a thin red clay horizon. The flows are all alkalic lava. The top two flows are identical feldspar-porphyritic alkalic basalt, and the bottom flow is transitional between alkalic basalt and hawaiite. All three flows probably erupted during the alkalic postshield stage. As on Ojin Seamount, these flows were clearly erupted subaerially.

Dalrymple and others (1980) obtained ^{40}Ar-^{39}Ar data from two samples recovered during drilling of DSDP site 432. Only one of the samples gave easily interpretable results, and that one indicated an age of 56.2±0.6 Ma.

Yomei Seamount (88).—DSDP Leg 55 drilled two holes at site 431 on a faulted terrace (Jackson and others, 1980). Neither hole reached volcanic basement. The upper 7.5 m consisted of fragments of manganese-oxide crust, authigenic silicates, phosphate, ice-rafted pebbles, and calcareous sand of Quaternary age. The lower 9.5 m consisted of authigenic silicates, manganese-oxide crust fragments, altered basalt clasts, and calcareous sand of middle Eocene age.

Suiko Seamount, southern part (90).—Saito and Ozima (1975, 1977) obtained a ^{40}Ar-^{39}Ar incremental-heating isochron age of 59.6±0.6 Ma for a single sample of mugearite dredged from the southern part of Suiko. The reliability of this age has been questioned, however, on the basis of (1) selection of the sample from a variety of ice-rafted material dredged from Suiko and (2) the unorthodox and potentially misleading treatment of the ^{40}Ar-^{39}Ar data (Dalrymple and others, 1980). Three conventional K-Ar determinations ranging from 22 Ma to 43 Ma on samples from the same dredged material (Ozima and others, 1970) are unreliable because of severe sample alteration. The sample of mugearite could represent lava of an alkalic postshield stage; however, the presence of abundant ice-rafted material (Ozima and others, 1970) creates obvious difficulties in identifying an indigenous sample from among the erratics.

Suiko Seamount, central part (91).—DSDP Leg 55 drilled a deep reentry hole (433C) in a lagoonal sediment pond (Jackson and others, 1980) on top of Suiko Seamount. The hole penetrated 550.5 m, the lower 387.5 m entirely in basalt. Samples of more than 100 flows or flow lobes were recovered, of which the upper three flow units are alkalic basalt and the remainder are tholeiitic basalt and picritic tholeiitic basalt. The three alkalic flows probably erupted during a postshield stage, whereas the thick sequence of tholeiitic lava represents the shield stage.

Dalrymple and others (1980) determined an age of 64.7±1.1 Ma for two samples of alkalic and tholeiitic basalt recovered during drilling of DSDP site 433C. The data were obtained by ^{40}Ar-^{39}Ar incremental heating.

Tenji Seamount (98).—A single dredge was obtained from Tenji Seamount by the U.S. Coast Guard Cutter *Glacier* in September 1971 (Bargar and others, 1975). The small group of rocks recovered included samples of basalt, crystal tuff, volcaniclastic sandstone, mudstone, graywacke, and a manganese nodule. Some of the lava samples could be derived from the seamount, but the rest are clearly glacial erratics. None of the samples was dated because of the uncertainty of their origin.

Meiji Seamount (108).—DSDP Leg 19 drilled site 192 on top of Meiji Seamount. A thickness of 13 m of pillow basalt with glassy margins was recovered; the rocks are highly altered, but interpretation of the immobile trace elements suggests that they are tholeiitic basalt erupted during the shield stage (Dalrymple and others, 1980b).

The only radiometric data available for Meiji is a minimum age of 61.9±5.0 Ma for highly altered basalt recovered during drilling of DSDP site 192 (Dalrymple and others, 1980b). This age is considerably less than the 70–68 Ma for overlying sediments based on nannoflora (Worsley, 1973).