TECTONICS, GEOCHRONOLOGY, AND ORIGIN OF THE HAWAIIAN-EMPEROR VOLCANIC CHAIN

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INTRODUCTION

The Hawaiian Islands—the seamounts, banks, and islands of the Hawaiian Ridge—and the seamounts of the Emperor Seamounts (Fig. 1) include 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 southeastern end; the volcanoes at the northwestern end are about 75 to 80 million years old. The volcanic ridge is surrounded by a symmetrical deep as much as 0.7 km deeper than the adjacent ocean floor (Hamilton, 1957). The deep is in turn surrounded by the broad Hawaiian Arch (see Plate 5).

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 or listed in Table 2. The Island of Hawaii includes the volcanoes of Mauna Loa, which last erupted in 1984, and Kilauea, which erupted in 1987. Loihi Seamount, located about 30 km off the southeast coast of Hawaii, is also active and considered to be an embryonic Hawaiian volcano (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 Seamount chain, which continues northward another 2,300 km.

It is now clear that this remarkable feature was formed during approximately the past 70 m.y. as the Pacific lithospheric plate moved first 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 floor as each volcano was progressively cut off from its source of lava and a new volcano formed 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 should also 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 not be related to the structure of the sea floor. Finally, the volcanic rocks of the volcanoes should be similar in both chemistry and sequence of eruption along the chain or should change in a systematic and coherent way.

In this section we describe the Hawaiian-Emperor volcanic chain. We review the evidence that indicates that all of the corollaries mentioned above are true and that the hot-spot hypothesis is therefore 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. This section is a condensed version of a paper by Clague and Dalrymple (1987) that includes (1) a more detailed description of the petrology and ages of the individual sampled volcanoes that compose the chain, and (2) a section on petrology of Hawaiian lava.

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. 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

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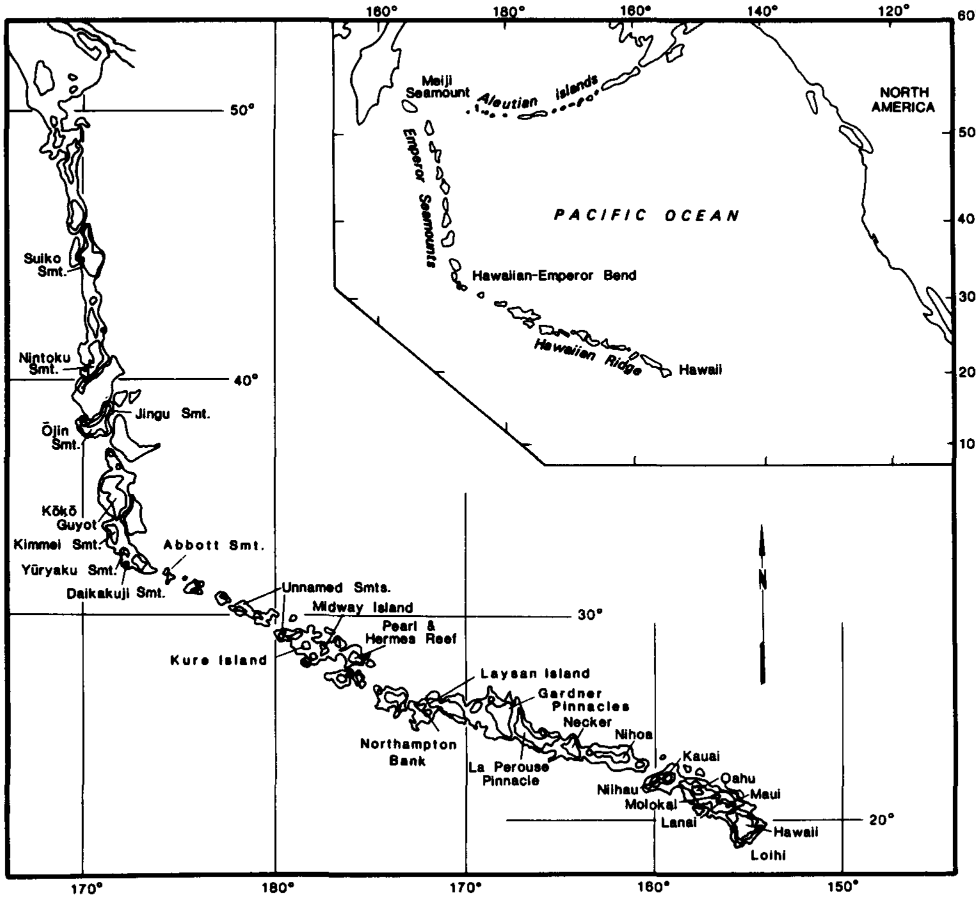

Figure 1. Bathymetry of the Hawaiian Emperor volcanic chain modified from Chase and others (1970). Inset shows the location of the chain in the central north Pacific. Contour interval is 1 km.

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 Ma (Fig. 3). Volcanoes between Midway and the Hawaiian-Emperor bend and in the Emperor Seamounts south of Jingu Seamount are all built on crust with an age between that of anomalies M0 and M3. Because the seamounts increase in age to the northwest, but the underlying crust is roughly constant in age, the age of the crust when the overlying volcano was built decreases systematically from about 80 Ma at the bend to about 55 Ma 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 Staff, 1978; Byrne, 1979).

If we extrapolate northward from Jingū Seamount, we estimate that the crustal age at Suiko Seamount was roughly 40 Ma and at the northernmost seamount, Meiji Seamount, was <20 Ma when those seamounts formed. If this extrapolation is extended beyond Meiji Seamount to hypothetical seamounts presumed to have existed once but to 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 90–100 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. 2). Several fracture zones—including the Mendocino, Murray, and Molokai—cross the

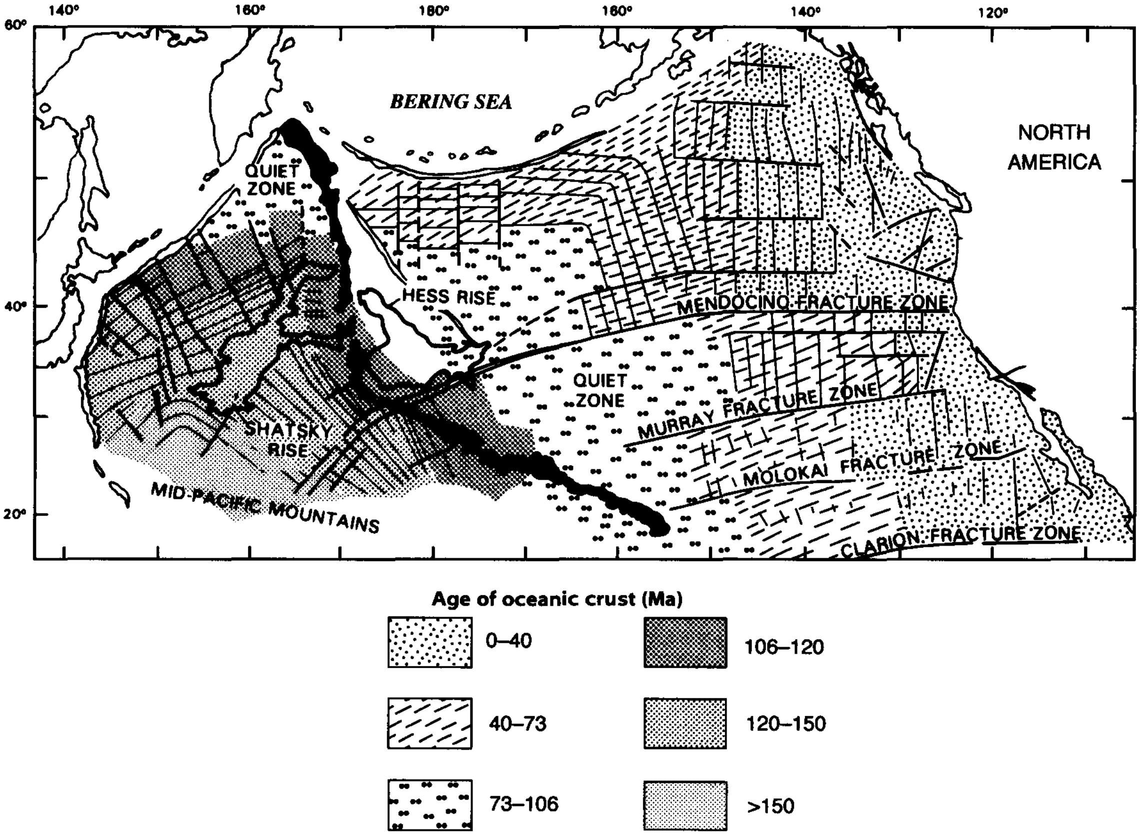

Figure 2. Crustal structure and age map of the north Pacific modified from Hilde and others (1976). The Hawaiian-Emperor chain crosscuts preexisting fracture zones and the Mesozoic magnetic anomaly sequence.

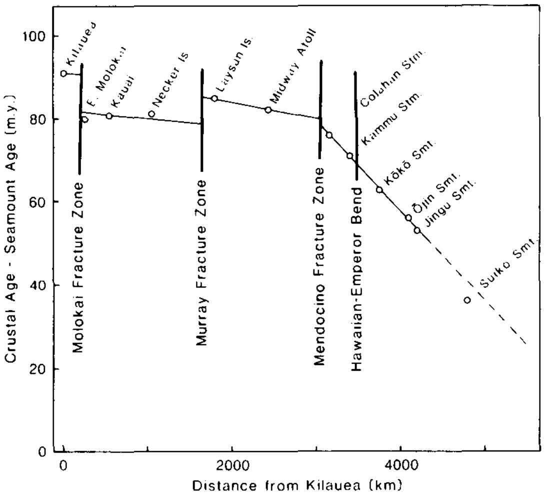

Figure 3. Plot of age of the oceanic crust when each overlying seamount formed as a function of distance from Kilauea. Offsets are at fracture zones. Along the Hawaiian chain both the crust and the volcanoes increase in age to the west so the crustal age when the volcanoes formed is roughly constant. On the other hand, the Emperor Seamounts increase in age to the north, but the crust decreases in age. The age of the crust when the seamounts formed decreases from roughly 75 m.y. at the bend to less than 40 m.y. at Suiko Seamount.

TABLE 1. HAWAIIAN ERUPTIVE PRODUCTS

Eruptive Stage	Rock Types	Eruption Rate	Volume (%)
Rejuvenated stage	Alkalic basalt Basanite Nephelinite Nepheline melilitite	Very low	<1
Postshield stage	Alkalic basalt Transitional basalt Ankaramite Hawaiite Mugearite Benmoreite Trachyte	Low	~1
Shield stage	Tholeiitic basalt Picritic tholeiitic basalt	High	95-98
Preshield stage	Basanite Alkalic basalt Transitional basalt	Low	~3

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 volume 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). The three later stages are well studied and documented (Stearns, 1940a, b, c; Macdonald and Katsura, 1964; Macdonald, 1968), but the preshield stage, which includes the early phase of the submarine history of the volcano, has only been examined recently (Moore and others, 1979, 1982).

In the shield stage, tholeiitic basalt flows construct the main volcanic edifice in the relatively short span of perhaps 10^6 years or less (Jackson and others, 1972). Wright and others (1979) independently propose 200,000 years as the duration of tholeiitic volcanism. Most of the mass of an individual volcano (95 to 98 percent) is formed from these voluminous eruptions. The shield stage may include caldera collapse and eruption of caldera-filling tholeiitic basalt. During the alkalic postshield stage, a relatively thin cap of alkalic basalt and associated differentiated lava may fill the caldera and cover 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 (< 1 percent) of SiO_2-poor lavas may erupt from isolated vents. This stage is commonly called the posterosional alkalic stage but is called the alkalic rejuvenated stage here. 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 2). Some of these ideas are more than a half century old. Cross (1915) recognized that each of the Hawaiian volcanoes built a shield of lava, comparable to Kilauea flows, during a period with frequent voluminous eruptions. He also noted that this period was followed by erosion during a period of declining activity that produced cinder cones 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 formed "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. The location, small size, seismic activity, and fresh, glassy lava all indicate that Loihi is an active volcano, the youngest in the Hawaiian-Emperor volcanic chain. Some of the older lava recovered from Loihi Seamount is alkalic basalt and basanite, whereas the youngest lava recovered is 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, and during declining activity the magma compositions revert to al-

TABLE 2. ERUPTIVE STAGES REPRESENTED ON VOLCANOES OF THE HAWAIIAN-EMPORER CHAIN*

Volcano No.	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	-	R	R	R
Leeward Islands and Hawaiian Ridge					
17	Nihoa	-	M	-	-
19	-	-	X(T)	-	-
20	-	-	X	-	X
21	-	-	X	-	-
23	Necker	-	M	X	X
26	La Perouse	-	X	-	-
28	Brooks Bank	-	X(T)	X	-
29	St. Rogatien Bank	-	-	X	-
30	Gardner	-	X	X	-
36	Laysan	-	-	X	-
37	Northampton Bank	-	X	-	-
39	Pioneer Bank	-	X	-	-
50	Pearl & Hermes Reef	-	-	X	-
51	Ladd Bank	-	-	-	X
52	Midway	-	M	X	-
53	Nero Bank	-	X	-	-
57	-	-	-	X	-
63	-	-	-	-	X
65	Colahan	-	X	-	X
65A	Abbott	-	X(T)	-	-
Emporor Seamounts					
67	Daikakuji	-	X	-	-
69	Yuryaku	-	X	X	-
72	Kimmei	-	-	X	-
74	Koko	-	X	M	-
76	Koko	-	X	-	-
81	Ojin	-	X	X	-
83	Jingu	-	-	X	-
86	Nintoku	-	-	X	-
90	Suiko	-	-	X	-
91	Suiko	-	M	X	-
108	Meiji	-	M	-	-

*For the volcanoes from Kilauea through Necker, the table is based on detailed mapping and sampling. The stages for the remaining volcanoes are represented primarily by dredge and drill samples.

Abundances:

A = known to be absent
M = major unit
R = rare or small-volume unit
X = present but extent unknown
- = no data

(T) = transitional lava that probably erupted during the late shield stage or the caldera collapse phase of the shield stage kalic 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, since it can occur either throughout the shield stage or near the beginning of the alkalic postshield stage. The lava erupted may therefore be tholeiitic, alkalic, or both.

GEOLOGY OF THE HAWAIIAN ISLANDS

Descriptions of the volcanoes and eruptions were made by nearly all the earliest visitors to the Hawaiian Islands. Descriptions of particular note are those of Archibald Menzies in 1793, William Ellis (1823), Lord George Byron in 1825, Joseph Goodrich (1826) to 1833, and Titus Coan from 1840 to 1882. Many of their letters describing the islands 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 1840–1841. 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 Jaggar (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 there appeared papers 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 lavas 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 studies—mainly descriptive and reconnaissance—were superseded by detailed mapping of the islands beginning in the 1930s. 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 geologic map of Kauai (Macdonald and others, 1960) completed the monumental mapping job begun by Stearns; though Stearns was not a coauthor of 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 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 derivation 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 Clague and Dalrymple (1987) were largely extracted from the above publications, but include additional unpublished observations by ourselves for Hualalai, East and West Molokai, Koolau, Kauai, and Niihau.

The maps of Stearns and coworkers separate rejuvenated stage lava from earlier lava, but they do not subdivide the 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 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 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 lavas. Alkalic postshield stage lava occurs late in the eruptive sequence and has not yet developed on Loihi, Kilauea, or Mauna Loa volcanoes. To the west 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).

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 and others, 1982), Kilauea, and Mauna Loa. Each of these calderas is connected to two prominent rift zones. Not all Hawaiian volcanoes, however, have 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, indicating 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 first applied to the area in the 1950s. Geological descriptions of the leeward islands include those of S. Powers (1920) for Nihoa and Necker islands and those of 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. Two drill cores were collected on Midway Atoll; the petrology of the basaltic basement is described by Macdonald (1969) and Dalrymple and others (1974, 1977), and the geology of the sites is detailed by Ladd and others (1967, 1970). Paleomagnetic data on flows and dikes from Nihoa and Necker islands are given by Doell (1972), and 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 1970s, 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, b) and Garcia and others (1987). Subsequent cruises to the area have been made by the Hawaii Institute of Geophysics and the U.S. Geological Survey (Clague and Dalrymple, 1987).

Lava from the Hawaiian Ridge and Emperor Seamounts is difficult to assign to volcanic stages because samples are recovered by dredging and drilling or are collected from small islets, and the field relations are usually unknown or only poorly known. Table 2 summarizes the available data from the Hawaiian Ridge. From the sequence and volumes of lava in the Hawaiian Islands, we have inferred 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. A number of 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 Clague and Dalrymple (1987). 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 alkalic 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 the lava 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 2). 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 it was Ozima and others (1970) who described the dredge samples first recovered in 1968 from Suiko Seamount. 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 on cruise ARIES Leg VII (Davies and others, 1971; 1972), DSDP (Deep Sea Drilling Project) Site 192 on Meiji Seamount (Creager and Scholl, 1973), DSDP sites 308 and 309 on Koko guyot (Larson and Moberly, 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 Seamount chain is derived from these two cruises. The petrology of lava 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 2 summarizes the available data on eruptive stages represented by samples from the Emperor Seamounts, and details are given in Clague and Dalrymple (1987) 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 Seamount chain. 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. This implies that 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 lava samples are alkalic basalt, hawaiite, mugearite, and trachyte similar to those erupted in the Hawaiian Islands, but those from Koko Seamount include anorthoclase trachyte and phonolite that are interpreted to have erupted during the alkalic postshield stage (Clague, 1974a). Alkalic lava of the rejuvenated 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 and bare of sediments and coral and that they 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.

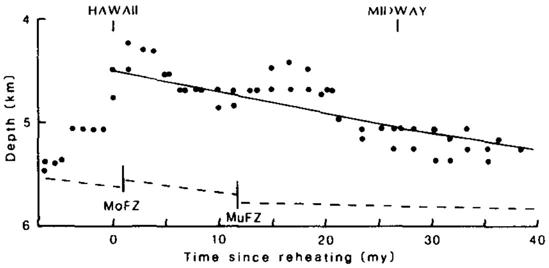

Figure 4. Minimum depth to the sea-floor swell as a function of time since reheating (or age of volcanoes along the chain) for the Hawaiian chain, from Detrick and Crough (1978) and Crough (1983). The dashed line is the predicted depth for normal aging of the lithosphere away from the spreading ridge. The solid line is the predicted depth for a thermally reset lithosphere 45 km thick. MoFZ and MuFZ are the Molokai and Murray fracture zones.

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 over time results from thermal aging of the lithosphere and from 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 the amount that 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 (ca. 80–120 Ma) for which the depth should be about 5.5 to 5.9 km. The depth near Hawaii, however, is less than 4.5 km (Fig. 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 primarily a function of their distance from the hot spot, i.e., 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, 1987). 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-gauge 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 0.3 m.y. and also indicate that the rate may have accelerated during that time (Moore and Fornari, 1984). Moore's (1970) tide-gauge data also show that absolute subsidence decreases systematically away from the Island of Hawaii, with absolute rates of subsidence of 1.7 mm/yr and 0 mm/yr for Maui and Oahu, respectively. Some of this decrease in subsidence may be caused by 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.

GEOCHRONOLOGY AND PROPAGATION OF VOLCANISM

Early work: Legends and degree of erosion

According to Hawaiian legend, the goddess Pele first inhabited Kauai and then moved eastward 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.

Not only was Dana the first geologist to conclude that the order of extinction of Hawaiian volcanoes was approximately from west to east, he also recognized that the Hawaiian chain included the islets, atolls, and banks that stretch for some distance to the west 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; Martin and Pierce, 1915; Cross, 1915; Wentworth, 1927; Hinds, 1931; Stearns, 1946), although the sequences they proposed invariably differed in detail. 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, 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 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:

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 Age

The first radiometric ages for Hawaiian volcanoes were determined by McDougall (1963), who measured ages of from 2.8 to 3.6 Ma for the upper and middle Waianae Volcanics on Oahu (all K-Ar ages have been converted to the new constants [Steiger and Jaeger, 1977]). McDougall also reported an age of 8.6 Ma for the Mauna Kuwale rhyodacite of the lower Waianae Volcanics, 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 seven of the principal Hawaiian volcanoes and concluded that the ages of the shield-building phases were approximately:

Kauai	5.8–3.9 Ma
Waianae	3.5–2.8
Koolau	2.3–2.6
W. Molokai	1.8
E. Molokai	1.5–1.3
W. Maui	1.3–1.15
Haleakala	0.8
Hawaii	<1

McDougall thus confirmed Stearns' extinction sequence and also suggested that the main shield-building phase 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 measured 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 (Table 3, and Clague and Dalrymple, 1987). Radiometric ages of two volcanoes on the Hawaiian Ridge, which are not included because it is probable that the samples are not from Hawaiian volcanoes (Clague and Dalrymple, 1975), 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) dredged from the northern slope of Necker Island.

In addition to the radiometric age data, paleontologic ages for several of the Hawaiian-Emperor volcanoes are based on material recovered by dredging and drilling programs. In general, these ages postdate volcanic activity and are consistent with the radiometric data. From east to west they include (1) an age of 28 to 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 west of Midway (Bukry, 1975); (2) an age of 15 to 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 the drill hole (the "reef hole") at Midway Atoll; (3) an age of 39 to 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 to 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 early Eocene (?) benthic foraminifers in sediments above basalt at DSDP Site 432 on Nintoku Seamount (Butt, 1980); (7) an age of 59 to 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 to 73 Ma for lower Maastrichtian nannofossils from sediments above basalt at DSDP Site 192 on Meiji Seamount at the northern end of the Emperor Seamount chain (Worsley, 1973).

None of these fossil ages is in conflict with the radiometric data. 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 (N22) (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 that no

TABLE 3. SUMMARY OF K-Ar GEOCHRONOLOGY ALONG THE HAWAIIAN-EMPEROR VOLCANIC CHAIN

Volcano No.	Name	Distance From Kilauea Along H-E Trend (km)*	Best K-Ar Age† (10^6yr)	Reference(s)	Remarks
1	Kilauea	0	>0 to 0.4	–	Historic 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	East Maui	182	0.75 ± 0.04	3	Samples from tholeiitic shield (Honomanu Basalt)
7	Kahoolawe	185	>1.03 ± 0.18	3	Samples from postshield alkalic stage (upper member 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	Sample from tholeiitic shield (Lower member 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)
17	Nihoa	780	7.2 ± 0.3	9	Samples from tholeiitic shield
20	unnamed	913	9.6 ± 0.8	20	Dredged samples of alkalic basalt
23	Necker	1058	10.3 ± 0.4	9	Samples from tholeiitic shield
26	La Perouse Pinnacle (French Frigates Shoal)	1209	12.0 ± 0.4	9	Samples from tholeiitic shield
27	Brooks Bank	1256	13.0 ± 0.6	20	Dredged samples of hawaiite and alkalic basalt
30	Gardner Pinnacles	1435	12.3 ± 1.0	20	Dredged samples of alkalic and tholeiitic basalt
36	Laysan	1818	19.9 ± 0.3	10	Dredged samples of hawaiite and mugearite

(Table 3 continues on next page)

conflict exists between the ages of the reef and that of the underlying volcanic basement of 1.8 to 2.7 Ma.

Two samples of Eocene terrigenous sediments 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 3 and plotted in Figure 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 exception is Abbott Seamount, a small volcano between Colahan and Kammu seamounts, which was not previously numbered and to which we have assigned number 65A.

As can be seen from the information in Figure 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). The data also show that the progression is continuous from Kilauea at least to Suiko Seamount, more than half-way up the Emperor Seamount 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 accurately determine 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 at least one radiometric age

TABLE 3. (continued)

Volcano No.	Name	Distance From Kilauea Along H-E Trend (km)*	Best K-Ar Age† (10^6 yr)	Reference(s)	Remarks
37	Northampton Bank	1841	26.6 ± 2.7	10	Dredged samples of tholeiitic basalt
50	Pearl & Hermes Reef	2291	20.6 ± 0.5	11	Dredged samples of phonolite, hawaiite, and alkalic basalt
52	Midway Islands	2432	27.7 ± 0.6	12	Samples of mugearite and hawaiite from conglomerate overlying tholeiitic basalt in drill hole
57	unnamed	2600	28.0 ± 0.4	11	Dredged samples of alkalic basalt
63	unnamed	2825	27.4 ± 0.5	11	Dredged samples of alkalic basalt
65	Colahan	3128	38.6 ± 0.3	13	Dredged samples of alkalic basalt
65A	Abbott	3280	38.7 ± 0.9	13	Dredged samples of tholeiitic(?) basalt
67	Daikakuji	3493	42.4 ± 2.3	14	Dredged samples of alkalic basalt
69	Yuryaku	3520	43.4 ± 1.6	11	Dredged samples of alkalic basalt
72	Kimmei	3668	39.9 ± 1.2	14	Dredged samples of alkalic basalt
74	Koko	3758	48.1 ± 0.8	14, 15	Dredged samples of alkalic basalt, trachyte, and phonolite
81	Ojin	4102	55.2 ± 0.7	16	Samples of hawaiite and tholeiitic basalt from DSDP Site 430
83	Jingu	4175	55.4 ± 0.9	17	Dredged samples of hawaiite and mugearite
86	Nintoku	4452	56.2 ± 0.6	16	Samples of alkalic basalt from DSDP Site 432
90	Suiko	4794	59.6 ± 0.6	18, 19	Single dredged sample of mugearite
91	Suiko	4860	64.7 ± 1.1	16	Samples of alkalic and tholeiitic basalt from DSDP Site 433

*From Bargar and Jackson (1974), and K. E. Bargar (written communication, 1978).

†Oldest reliable age of tholeiitic basalt, where available. All data have been converted to the new constants $\lambda_\varepsilon + \lambda_\varepsilon{}' = 0.581 \times 10^{-10}\ \mathrm{yr}^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10}\ \mathrm{yr}^{-1}$, $^{40}\mathrm{K/K} = 1.167 \times 10^{-4}$ mol/mol.

References:

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, unpublished data
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, 1987

on lava flows erupted during one or more stages of volcanic activity. 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 shield-building (tholeiitic) volcanism. For Table 3, 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 to 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 part of the chain. The question of which ages to use is 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

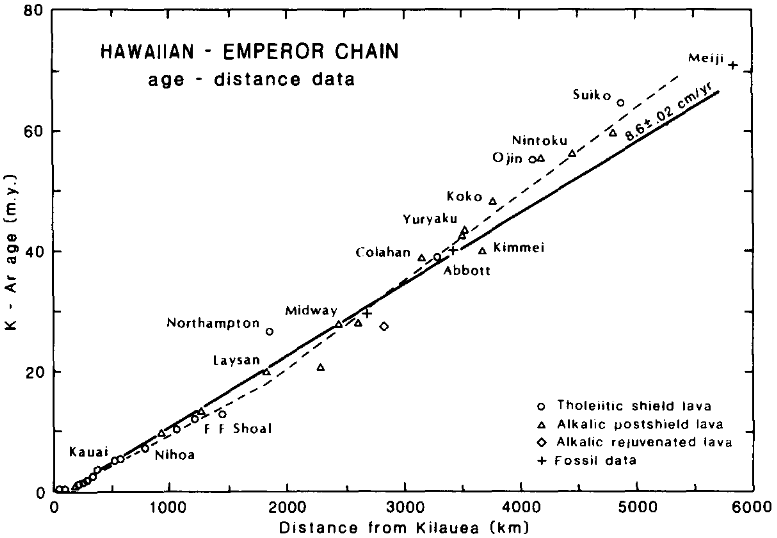

Figure 5. Age of volcanoes in the Hawaiian-Emperor chain as a function of distance from Kilauea. The solid line is the least-squares cubic fit (York-2) from Table 4 and represents an average rate of propagation of volcanism of 8.6 ± 0.2 cm/yr. Dashed line is a two-segment fit using the data from Kilauea to Gardner and Laysan to Suiko (Table 4). Radiometric data from Table 3; paleontologic data discussed in text.

younger than the tholeiites, 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 alkalic and late-stage tholeiitic lava is only a few hundred thousand years in the Hawaiian Islands (McDougall, 1964, 1969; McDougall and Swanson, 1972; Funkhouser and others, 1968; Doell and Dalrymple, 1973) and, presumably, in the other volcanoes of the Hawaiian-Emperor chain. For one unnamed volcano on the western Hawaiian Ridge (no. 63), the only data available are from the rejuvenated stage. In the principal Hawaiian Islands the eruption of rejuvenated stage lava may postdate the tholeiitic shield and alkalic postshield stages by more than 4 m.y. (McDougall, 1964; G. B. Dalrymple, unpublished data), so the main shield of volcano no. 63 may be several million years older than indicated in Table 3.

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 disadvantage that they presume no error in distance and do not take into account the experimental errors of individual data.

We have treated the data in Table 3 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 3. 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 4. For the entire chain, the average rate of volcanic propagation is 8.6 ± 0.2 cm/yr, with an intersection (theoretical zero time) 89 km west 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, i.e., Kilauea through Abbott, have been calculated using both the maximum and minimum ages of tholeiitic volcanism. The results do not vary with model; they 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 some-

TABLE 4. RATES OF PROPOAGATION OF VOLCANISM ALONG SEGMENTS OF THE HAWAIIAN-EMPEROR CHAIN FOR SEVERAL LINEAR REGRESSION MODELS[*]

Chain Segment	Data	Simple Regression[†]		
		Unreconstructed	Forced Through Origin	York 2 Fit[§]
Hawaiian-Emperor	Table 3	7.8 ± 0.2 (175, 0.992)	8.2 ± 0.1	8.6 ± 0.2 (89)
Hawaiian chain	Table 3 (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)
	Clague and Dalrymple, 1987 (minimum ages)	8.6 ± 0.3 (119, 0.986)	9.1 ± 0.2	9.1 ± 0.3 (97)
Emperor Chain	Table 3	6.5 ± 0.8	7.9 ± 0.2	7.2 ± 1.1
Kilauea-Gardner	Table 3	9.9 ± 0.3 (57, 0.992)	10.6 ± 0.3	9.6 ± 0.4 (73)
Laysan Suiko	Table 3	6.9 ± 0.4 (0.971)	8.1 ± 0.2	6.8 ± 0.3
Gardner-Waianae	Table 3	9.5 ± 0.4 (54, 0.993)	10.1 ± 0.2	10.1 ± 0.8 (9)

[*] Rates are given in cm/yr. The intercept in km and the correlation coeffieient, r, are given in parentheses where relevant.

[†] Age on distance, unweighted data.

[§] Two error cubic, weighted data.

what higher than the rates calculated from either the maximum or minimum data, but the difference is largely a consequence of differences in the data sets, the ones in Table 3 being more current.

Rates calculated for the Emperor chain, i.e., 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 assume to be 3,451 km from Kilauea at the position of volcano no. 68. The predicted ages for the bend are 36.7 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 4, Fig. 5). The two former lines intersect near Garner Pinnacles at an age of about 18 Ma. Epp (1978) concluded that a rate change occurred at 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 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, but 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 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 3, Fig. 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 Island and Pearl and Hermes Reef as well as Midway Islands and Northampton Bank. Indeed, Mauna Loa, Kilauea, and Loihi, which are currently active and erupting tholeiitic basalt, 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 west of Kilauea (Table 4) 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 the tholeiitic shield, alkalic postshield, and alkalic rejuvenated stage volcanism for the principal Hawaiian volcanoes in Figure 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—shield or postshield—is chosen to represent the "age" of the volcanoes. Furthermore, a bias toward younger ages for the less eroded volcanoes, presumably Kilauea through East Maui, 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.

Even though 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 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 hotspot mechanism.

CAUSE OF THE ALKALIC REJUVENATED STAGE

A separate problem is the cause of the alkalic rejuvenated stage. Jackson and Wright (1970) used tide gauge data from Moore (1970) to suggest that generation of the rejuvenated stage Honolulu Volcanics might have been caused by uplift as Oahu 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 decreases systematically from nearly 2.5 m.y. on Niihau to <0.4 m.y. at Haleakala (see Fig. 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 alkalic 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 to 225 km to the east. Likewise, the Honolulu Volcanics on the Koolau Range of Oahu began erupting during formation of the East Maui shield located 160 km to the east. The rejuvenated stage Kalaupapa Volcanics on East Molokai erupted during formation of the Mauna Kea shield located 200 km to the east. Finally, the rejuvenated stage Hana Volcanics on East Maui began erupting during formation of the Mauna Loa shield located 160 km to the east. In each case, the rejuvenated stage lava began erupting during formation of a large shield 190 ± 30 km to the east. 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 rejuvenated stage magma generation is the rapid change from subsidence to uplift as the volcanoes override the flexural arch created by formation of the large shields. To the west of the

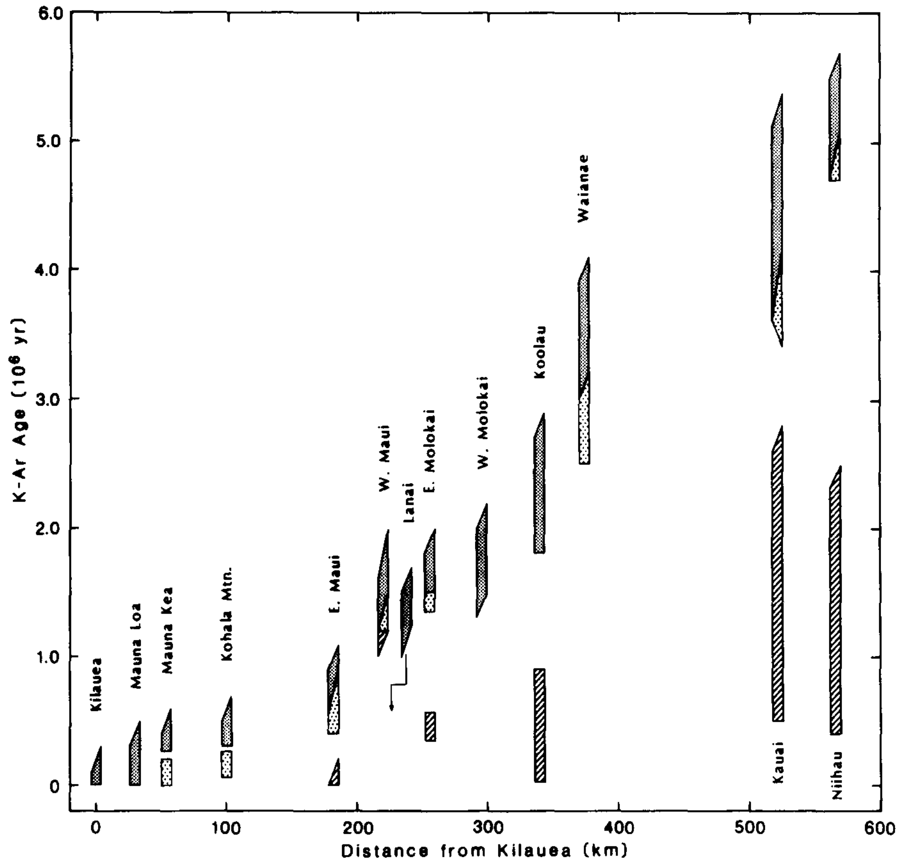

Figure 6. Known durations of tholeiitic shield stage (shaded), alkalic postshield stage (stippled), and alkalic rejuvenated stage (hatchured) volcanism for dated volcanoes of the principal Hawaiian Islands. Angled lines indicate overlapping or uncertain ages, or overlapping volcanism. Data from sources discussed in Clague and Dalrymple (1987). Data for Niihau and for the Koloa Volcanics on Kauai are unpublished.

Hawaiian Islands the rates of volcanic propagation were slower and more constant; we predict that rejuvenated stage lava there will be found to postdate the shield building stage by 2–3 m.y. We also suggest that the apparent paucity of rejuvenated stage lava to the west of the Hawaiian Islands may reflect the lack of large volcanic edifices capable of flexing the lithosphere sufficiently. Likewise, lack of any rejuvenated stage lava from the Emperor Seamounts may reflect 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.

ERUPTION RATES ALONG THE CHAIN

The bathymetry of the chain as a whole is not well known, particularly for the western Hawaiian Ridge; the 1970 charts for the North Pacific (Chase and others, 1970) and their derivative (U.S. Naval Oceanographic Office, 1973) are probably still the best published sources available. An updated bathymetric chart for the Emperor Seamounts (Clague and others, 1980b) 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 bathymetric data. The gross structure of the Emperor Seamounts is little changed in the later charts, but the

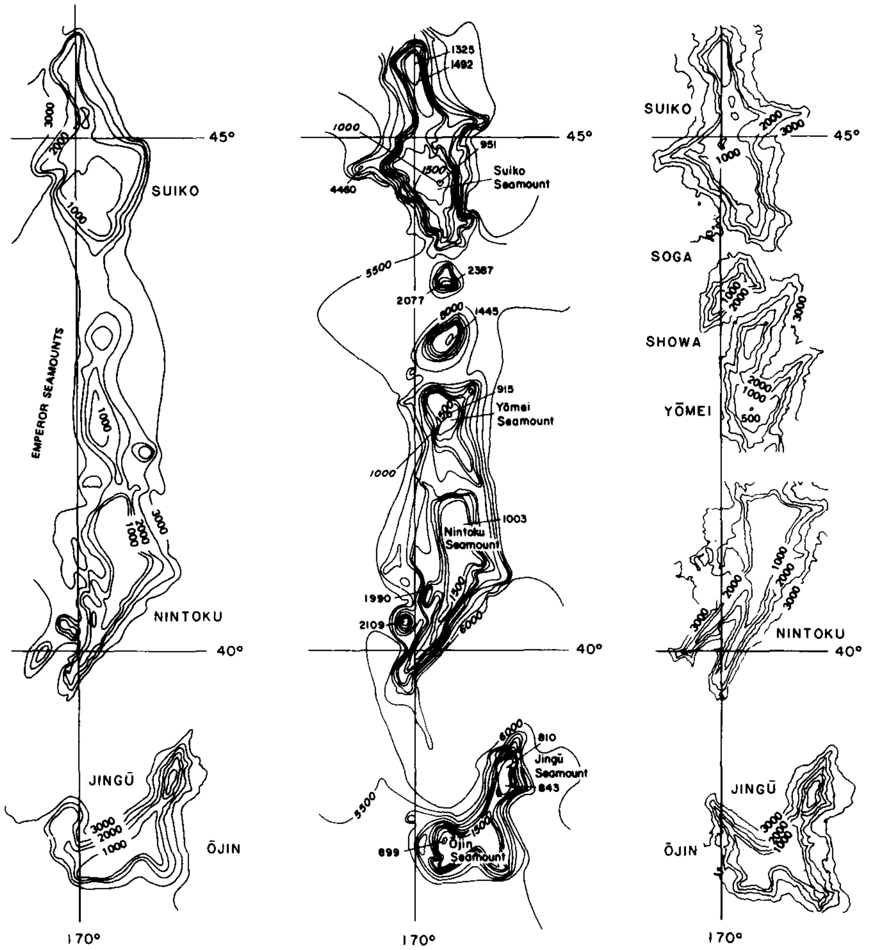

Figure 7. Comparison of bathymetry of the central Emperor Seamounts from Chase and others (1970) (left), Clague and others (1980b) (center), and Smoot (1982) (right). The general sizes and shapes of the various seamounts were fairly well mapped by bathymetric sounding, but the multibeam bathymetry adds a wealth of detail. Contour intervals are 500 fathoms for left and right figures and 500 m for center figure.

shapes and locations of some individual volcanoes change dramatically (Fig. 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 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, and these data are summarized in Table 5. Also listed are dx/dt, where t is time, calculated from the age relations along the chain and the derived quantity

TABLE 5. ERUPTIVE RATES ALONG THE CHAIN

	Volume/distance* dV/dx (x 10^3 km^3/km)	Propagation Rate† dx/dt (km/m.y.)	Eruption Rate dV/dt (x 10^4 km^3/m.y.)
Kilauea (1956-1983)§	—	—	8.6
Kilauea to Hualalai	1.15	250	29
Hualalai to Waianae	0.40	101	4.0
Hawaiian Islands (0-5.5 Ma)	—	—	5.6
Waianae to Gardner Pin.	0.19	101	1.9
Gardner Pin. to vol. 57	0.20	68	1.4
Vol. 57 to H-E Bend	0.02	68	0.1
Emperor Seamounts	0.16	72	1.2
Avg. Entire Chain	—	—	1.3

*From Figure 8.

†All but Kilauea to Hualalai from Table 4.

§From Dzurisin and others (1984), based on a combined eruption/intrusion rate.

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 further 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 the greatest volumes of lava at the greatest eruption rates in its 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.

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 from 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 refer-

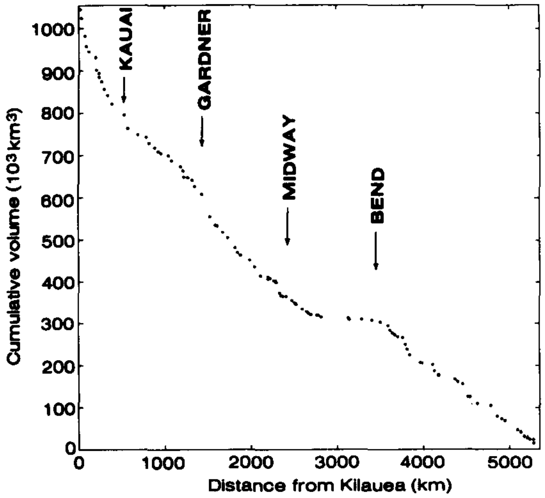

Figure 8. Cumulative volume along the Hawaiian-Emperor chain plotted as a function of distance from Kilauea (along the trend of the chain). The average dV/dx for the Emperor chain is 0.16 × $10^3$$km^3$/km. There is a segment of very low volcanic productivity to the east of the bend in which only 0.02 × $10^3$$km^3$/km was erupted. The remainder of the submarine portion of the Hawaiian chain has an average dV/dx of 0.20 × $10^3$$km^3$/km. In the Hawaiian Islands the section from Kauai to East Maui can be fit by 0.40 × $10^3$$km^3$/km and from East Maui to Kilauea by 1.1 × $10^3$$km^3$/km.

TABLE 6. PALEOLATITUDES FOR VOLCANOES OF THE HAWAIIAN-EMPEROR CHAIN AS DETERMINED FROM PALEOMAGNETIC MEASUREMENTS ON LAVA FLOWS AND FROM SHIPBOARD MAGNETIC SURVEYS
(Data from compilations by Kono [1980] and Sager [1984])

Volcano				
Name	No.	Number of Flows	Present Latitude (°N)	Paleolatitude (°N)
Kilauea, Mauna Loa Hualalai (historic)	1, 2, 4	17	19.5	19.6 ± 1.4
Kilauea, Mauna Loa Mauna Kea (^{14}C dated)	1, 2, 3	8	19.5	17.7 ± 10.7
Koolau	12	33	21.4	16.8 ± 3.6*
Waianae	13	55	21.5	15.7 ± 3.3*
Kauai (Makaweli Member)	14	25	22.0	15.6 ± 3.1*
Kauai (Napali Member)	14	46	22.1	14.9 ± 3.1*
Nihoa	17	14	23.1	21.0 ± 6.6
Midway	52	13	28.2	15.4 ± 5.4
Abbott	65A	†	31.8	17.5 ± 2.4*
Ojin	81	6	38.0	17.6 ± 13.2
Nintoku	86	4	41.3	36.0 ± 24.6
Suiko	91	†	44.8	16.7 ± 5
Suiko	91	65	44.8	27.1 ± 3.5*
Meiji	108	6	53.0	19.2 ± 4.1

*The more reliable data (Sager, 1984) are marked with an asterisk. Uncertainties are the values of $\alpha 95$.

†Shipboard magnetic survey.

ence with respect to the spin axis, particularly in early Cenozoic and late Cretaceous times, is not established.

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 hotspot (and thus the worldwide hotspot 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 seem to indicate, however, that there was motion between the hot spot and the spin axis, i.e., 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 6 and plotted in Figure 9 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 Kono (1980), Jackson and others (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 paleosecular 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 in 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

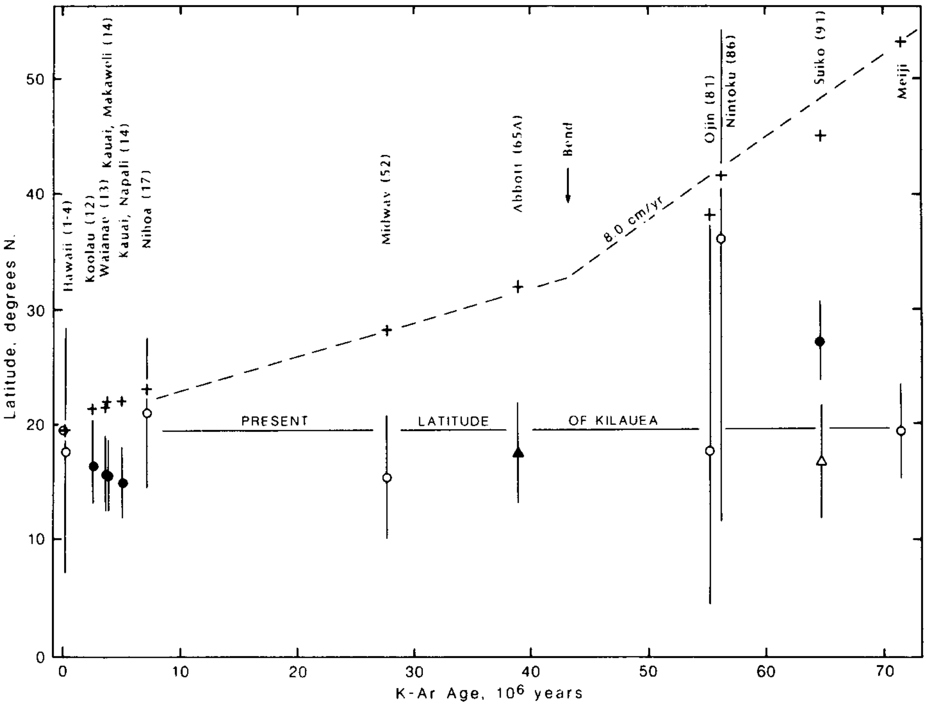

Figure 9. Paleolatitude versus age for volcanoes along the Hawaiian-Emperor chain. Crosses indicate present latitude; dots and circles indicate paleolatitudes determined from paleomagnetic data; triangles indicate paleolatitudes determined from shipboard magnetic surveys. The more reliable data are indicated by filled symbols. Error bars are α_{95}. Dashed reference line is the backtracked position of the hot spot relative to the Pacific plate, assuming a constant velocity of 8 cm/yr. Paleomagnetic data from Table 6; age data from Table 3 and Clague and Dalrymple (1987).

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 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 6. 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 rejuvenated stage flows that were erupted several million years after the hot spot had moved (relatively) eastward 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. 9) 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 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. 9) 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 6) 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 is 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).

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 between about 65 and 75 Ma the paleoequator was 10°–16° farther north than at present (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) pointed out that carbonate buildups in the Pacific can be divided into the bryozoan-algal and the 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. 10). 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.

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, because 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, i.e., true polar wander, during the latest Cretaceous and earliest Tertiary (for example, Morgan, 1981; Gordon and Cape, 1981; Jurdy, 1981, 1983; Gordon, 1982).

The paleolatitude of 17.5°N. ± 4.4° found for Abbott Sea-

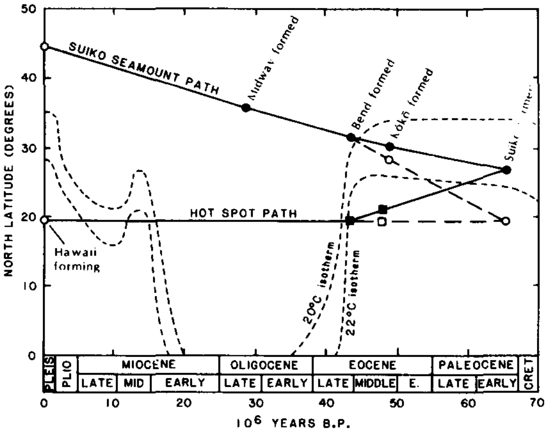

Figure 10. Approximate position of the 20°C and 22°C surface-water isotherms in the north-central Pacific during the Cenozoic, modified from Greene and others (1978), based on data of Savin and others (1975). Dots are the paleolatitudes of Suiko Seamount assuming that Suiko formed at 27°N. and that the hot spot has been fixed since the time of the bend. Circles are paleolatitudes assuming a fixed hot spot for the past 65 m.y. Squares show the positions of formation of Koko Seamount and the bend under the 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 the approximate boundary between the coral-algal (warmer) and the bryozoan-algal (colder) facies of Schlanger and Konishi (1975).

mount 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, i.e., after 43 Ma. This requires approximately 7.6° of southward latitudinal motion of the hot spot between 65 and 43 Ma and 5° of northward motion of the Pacific plate in order to satisfy the relative motion of about 0.65° lat/m.y. indicated by the age-distance data.

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; Jarrard and Clague, 1977; Jackson, 1976; 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 exhibits roughly north-trending orientations and apparently formed by the same mechanism between at least 80 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 have 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° from that predicted, implying motion of the Marquesas hot spot to the northeast with respect to the hot-spot reference frame at several cm/yr (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).

An especially knotty problem over the past decade has been the exact 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 (ca. 60°) change in the absolute motion of the Pacific plate. Because 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 may correlate with circum-Pacific tectonic events (Jackson and others, 1972; Clague and Jarrard, 1973; Moore, 1984), may be caused by the collision of India and Eurasia (Dalrymple and Clague, 1976), or 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 made.

A major feature of the northeast Pacific magnetic-anomaly pattern is the major change in the trend of the magnetic anomalies, i.e., 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 Staff, 1978; Byrne, 1979). This occurred perhaps as early as the time of 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 LaBrecque 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 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) further suggested 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, and (4) mechanical injection of heat into the lithosphere.

Propagating fracture hypothesis

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 en 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 en 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 NNE and SSW. He proposed that the Hawaiian volcanoes erupted along strike- 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, i.e., 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 perodititic material from the asthenosphere into the lithosphere (Fig. 11a and 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. 11c and 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

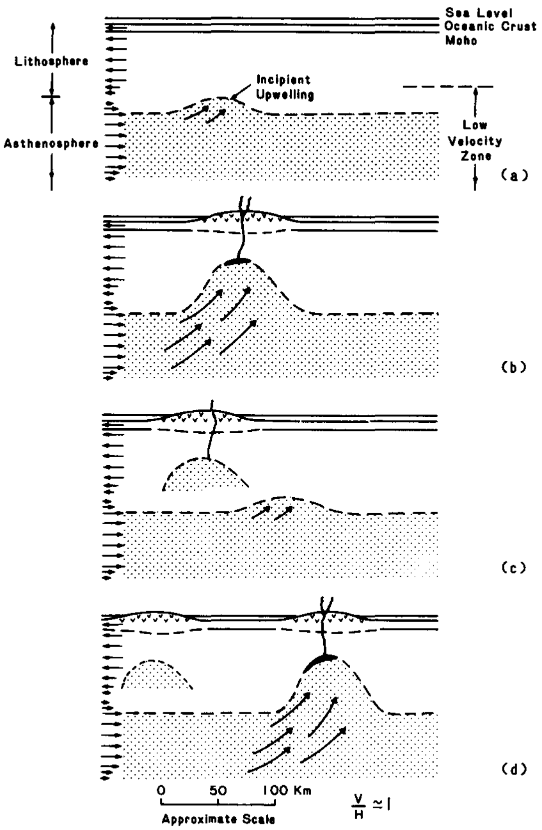

Figure 11. Schematic diagram of McDougall's (1971) propagating fracture hypothesis. A propagating tensional fracture allows diapiric upwelling from the asthenosphere (a) and partial melting, (b) relative motion between the lithosphere and the asthenosphere (arrows along left margin) eventually decapitates the diapir (c), and the cycle begins at a new position (d). The shaded zone represents peridotitic material that is the source rock of the lava.

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; however, it might be locally important and might explain the detailed distribution of volcanoes within the Hawaiian chain (Walcott, 1976).

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 en echelon in a clockwise sense in the Hawaiian chain and in a counterclockwise sense in the Emperor Chain (Fig. 12) (the latter conclusion, however, 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, i.e., in the orientation of the volcanic loci, which represent the injection of magma along lines perpendicular to least principle stress directions. On the basis of their analysis of the Hawaiian-Emperor, Pratt-Welker, Tuamotu, and Austral-Ellice-Gilbert-Marshall chains, Jackson and Shaw 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 NE-SW direction. Before the time of the bend, the rotational couple was left lateral, and the minimum stress was oriented NNE-SSW. 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

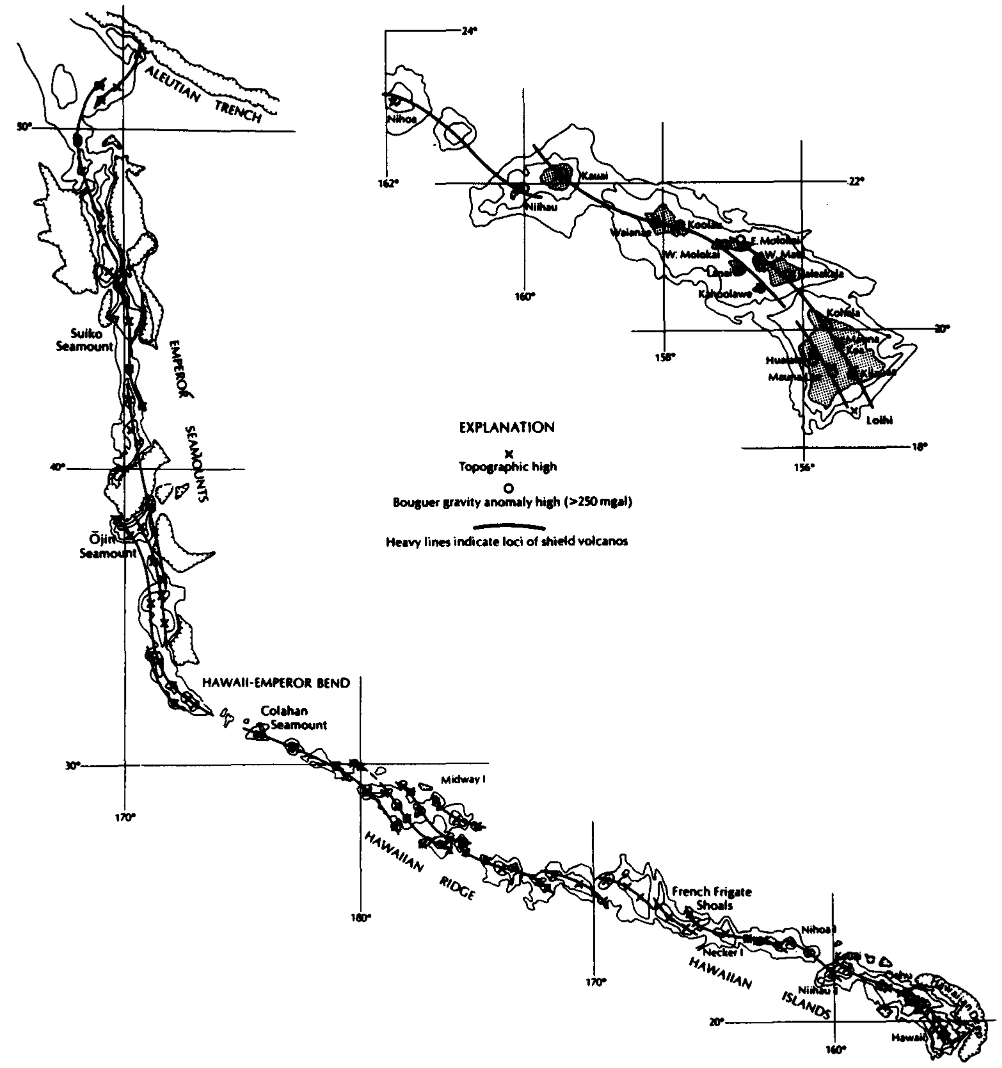

Figure 12. Loci of shield volcanoes in the Hawaiian-Emperor chain according to Jackson and others (1972). Inset shows the detailed relation between topographic highs, Bouguer gravity anomaly highs, and loci. Contour interval is 1 km; hachures indicate areas of closed lows.

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 of why Hawaii is located where it is. In addition, passive mantle upwelling seems inadequate to produce the enormous volume of lava that composes 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. 13a). 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. 13b and 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 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).

The plastic and brittle failure mechanisms proposed by Turcotte and Oxburgh provide a means of propagating a fracture as a function of plate motion, and each 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 "thermal" distance 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, it does not provide any insight into the lava-producing mechanism.

Convection hypothesis

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 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 swell, 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 Wilson (1962) did not discuss the Hawaiian chain, he showed it to be coincident with an early Tertiary ridge that he suggested formed by diverging convection cells.

Wilson (1963a, b, c, and 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. 14). 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.

The hypothesis that has undoubtedly received the most attention since Wilson's is that of Morgan (1971, 1972a and b),

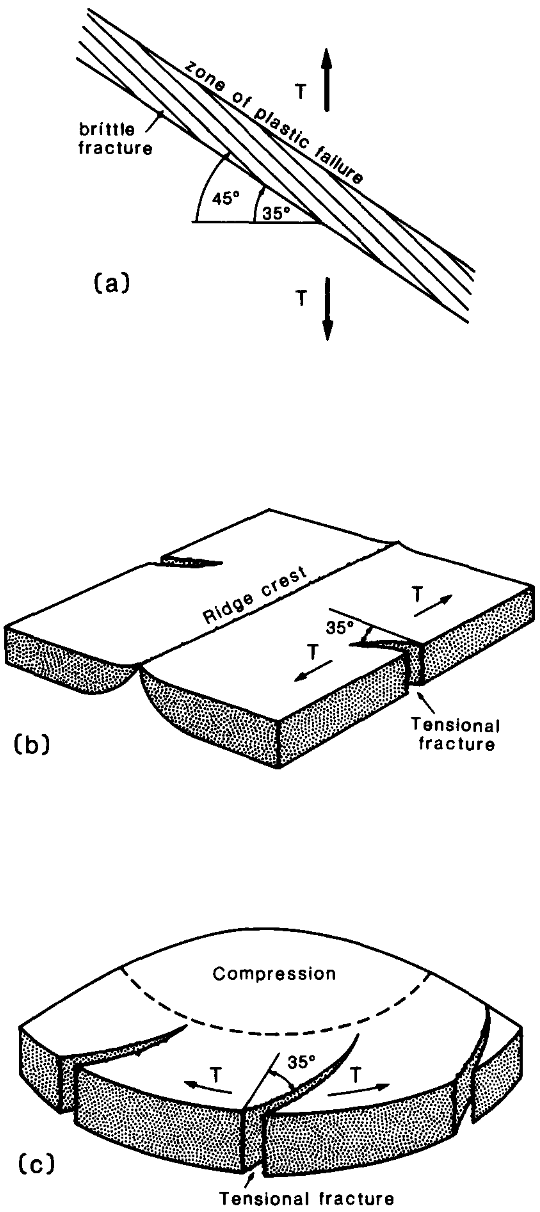

Figure 13. (a) Orientation of plastic and brittle failure in a thin plate under tension according to Turcotte and Oxburgh (1973, 1976, 1978). Tensional stress in lithospheric plate could be due to (b) cooling and thickening of the plate away from a spreading ridge, or (c) membrane stresses in a northward-moving plate on the oblate earth.

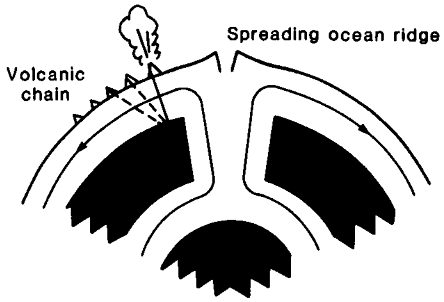

Figure 14. Wilson's proposed origin of the Hawaiian Island chain. The diagram shows that if lava is generated in the stable core of a mantle convection cell, and the surface is carried along by plate motion, then one source can give rise to a chain of successive extinct volcanoes. (From Wilson, 1963a, by permission of the National Research Council of Canada).

who proposed that the Hawaiian and other Pacific hot spots are narrow thermal upwellings, which he termed plumes, that originate deep within the Earth's mantle, possibly near the core. They arise because of the 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, are about 150 km in diameter, and convect upward at a rate of about 2 m per year. 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 (e.g., 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 hotspots 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, b) 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 voclanic 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 of non-hot spot bumps. Strong (1974) noted that the compositions of Kilauea and Mauna Loa lavas 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/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, which constitute "frozen" plumes. 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 "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 temporarily halt magma generation. However, one would think that the frozen chemical inhomogeneities should be seismically detectable.

Richter (1973) and Richter and Parsons (1975) have suggested that the Hawaiian-Emperor 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. 15). The time for the transition to occur depends on the spreading velocity but may be as short as 20 m.y. for a fast (i.e., 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 following a change in spreading direction. The age data for the Hawaiian-Emperor chain (Fig. 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).

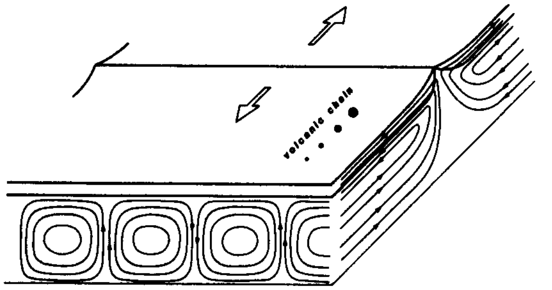

Figure 15. Schematic diagram of the large-scale asthenospheric flow related to sea-floor spreading and the superimposed small-scale longitudinal rolls, from Richter and Parsons (1975). A volcanic chain might occur in the zone of tension between diverging rolls and would propagate opposite to the direction of spreading.

Presnall and Helsley (1982) proposed a different type of convection model in which hot spots are caused by rising diapirs of depleted peridotite which transport enough heat to the base of the lithosphere to initiate melting. The depleted peridotite is produced at spreading centers as partial melt residua and is then recycled into the deep mantle at subduction zones. The depleted peridotite has a higher Mg/Fe ratio than the surrounding less depleted mantle, becomes gravitationally unstable, and rises as diapirs. The most bouyant diapirs would be the most depleted and would provide only a heat source, whereas the asthenosphere and lower lithosphere would be the source material for the magmas. This model is not supported by the rare-gas data which indicate that at least one component of the source is relatively primitive undegassed mantle.

Shear melting hypothesis

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. 16). 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 begins, the residua sinks, forming a kind of "gravitational anchor" that reaches down into the mantle, perhaps to the core-mantle boundary (Fig. 17). 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

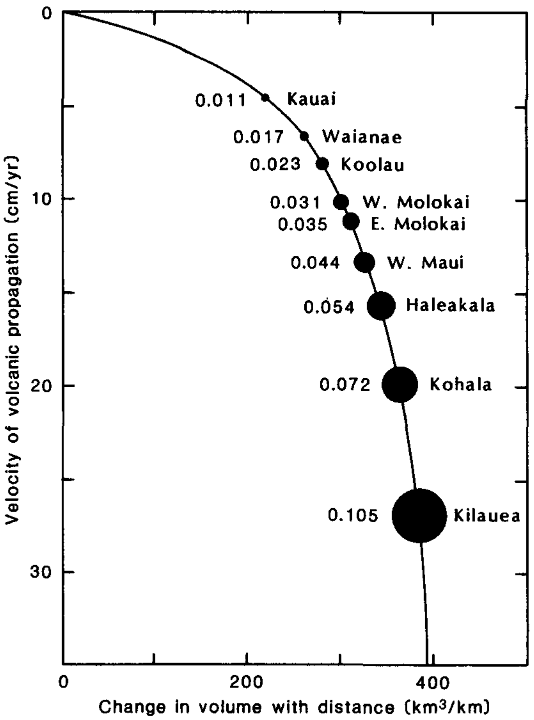

Figure 16. Change in volume of lava with respect to unit distance versus change in distance with respect to time (velocity of volcanic propagation) for the principal Hawaiian Islands, from Shaw (1973). The diameter of the circles is approximately proportional to the apparent eruption rates, which are also given in km^3/yr next to the circles.

(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.

Mechanical 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 for more than three decades has been attributed to some sort of thermal anomaly (e.g., 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 crust. 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). Detrick and Crough 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, i.e., 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 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).

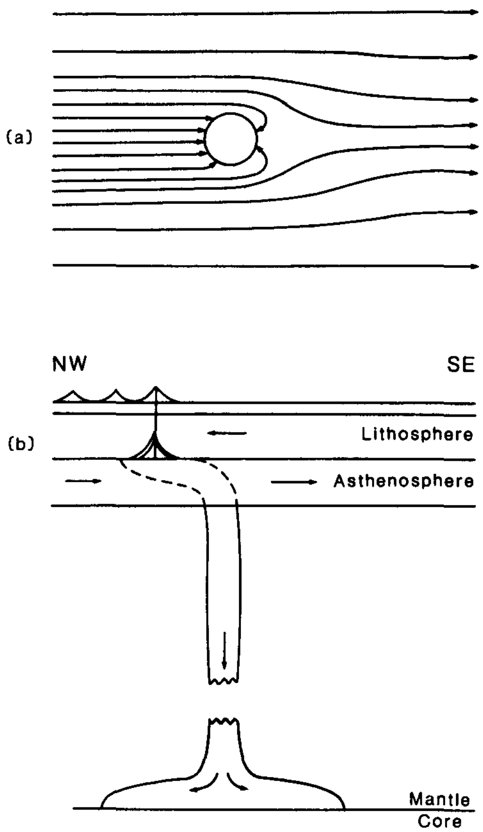

Figure 17. Schematic views of possible downwelling of dense residua from tholeiitic melting, from Shaw and Jackson (1973). (a) Plan view showing hypothetical flow lines in the asthenosphere along a horizontal plane taken at a time near the culmination of a melting episode. (b) Vertical section showing the proposed gravitational anchor.

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 require 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 "subduction" of the lower lithosphere thought to be one component of the source of ocean-island basalts. For Hawaii, the proposed depth of delamination, i.e., 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 P-T relations that the descending slab would not melt (and if it did the residua would rise rather than sink). Unless the lithosphere-asthenosphere boundary is a purely mechanical one (i.e., there are no compositional differences across the boundary), Hawaiian basalt would have to be generated from the material of the upper asthenosphere albeit at lower lithosphere depths.

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 upwells beneath the lithosphere. Petrologic studies indicate that Hawaiian lavas are generated from mantle sources consisting of at least three geochemical components; one of these is a primitive undegassed component. The precise 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 range of Hawaiian lavas.

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