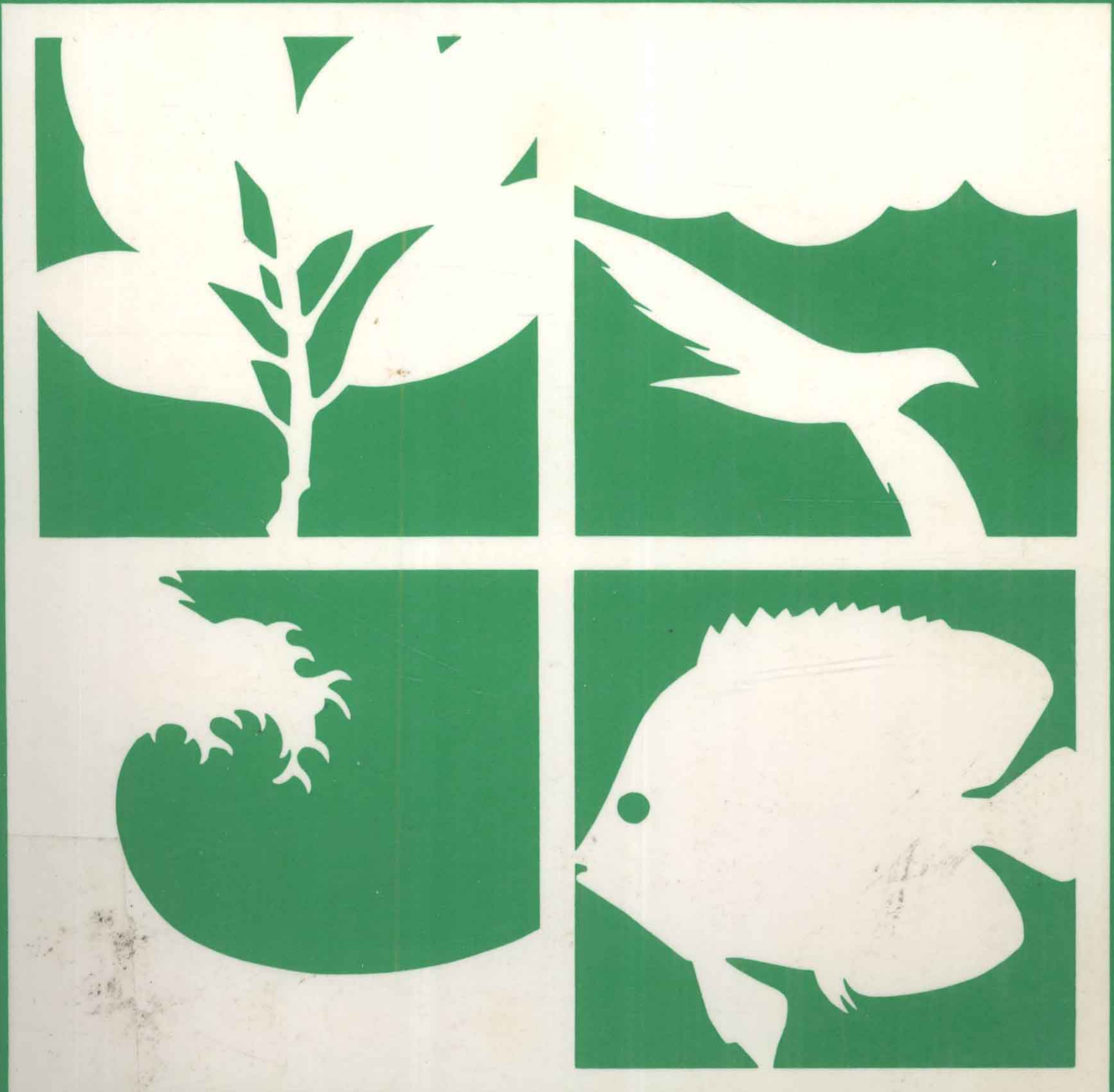
A Natural History of the Hawaiian Islands

Selected Readings II



Edited by E. Alison Kay

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University of Hawai'i
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For Beatrice Krauss

Who loves, studies, teaches and seeks to preserve

the natural history of Hawai‘i Nei

PREFACE

This second edition of *A Natural History of the Hawaiian Islands: Selected Readings* has been prompted by many expressions of interest in Hawaiian natural history by students, teachers, scientists, and visitors in Hawai'i, who need easy access to primary source material on major aspects of the natural history of the islands.

In 1972, *Selected Readings* reflected then-current thinking about the natural history of the Hawaiian Islands: descriptive geological history, classical inventories of biogeographical distribution, and some tentative ideas about the evolutionary processes that led to the formation of a biota even richer than that of the Galápagos. In the 20 years since the publication of the first edition, our thinking about the geological history of the Pacific basin has been revolutionized, and our conceptions of the course of Darwinian evolution have undergone significant changes. The Hawaiian Islands have provided much of the impetus for these changes in thought. Nor is it a small matter that the literature on Hawaiian natural history has increased manyfold since 1972. In a 1990 review article on volcanology (Walker 1990), 90% of the references were published after 1970. A random sampling from a bibliography of Hawaiian flowering plants (Mill et al. 1988) indicates nearly 50% of the articles are post-1970, and 70% of the references in a 1987 paper on the drepanidine birds (Freed et al. 1987) are post-1970.

It is not possible in one series of selections to do justice to the array of work now available on Hawaiian natural history. To bring some cohesion and pattern to the few papers selected, six major topics are recognized under which these readings in Hawaiian natural history are arranged — history and process, the terrestrial environment, the marine environment, evolution and endemism, ecosystems, and the effects of humans past and present. The book is intended to reveal a kind of large-scale evolutionary pattern that emphasizes the dynamics of the geological history of the islands, the uniqueness and fragility of the biota, and, most of all, the fact that the Hawaiian Islands are a very special place.

I am deeply grateful to the many people who have pointed out appropriate articles for inclusion, to authors who have written especially for this volume, and to both authors and publishers who have permitted us to reprint their works.

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Section 1

THE HAWAIIAN ISLANDS AND THE PACIFIC BASIN
HISTORY AND PROCESS

INTRODUCTION

> Among the groups of Polynesia, the Hawaiian Islands exceed all others in geological interest. The agency of both fire and water in the formation of rocks is exemplified not only by results, but also by processes now in action; and the student of nature may watch the steps through the successive changes. He may descend to the boiling pit and witness the operations in the vast laboratory, with the same deliberation as he would examine the crucible in a chemist's furnace. Thus the manner in which mountains are made, and islands built up, becomes a matter of observation.
>
> ---J.D. Dana, 1849

The theory of global plate tectonics took final form in the 1960's and has resulted in a substantive change in our ways of thinking about geological history. The Hawaiian Islands played a major role in the development of the theory when J. Tuzo Wilson proposed that the Hawaiian volcanoes were formed as the lithosphere beneath the Pacific Ocean moved slowly over a fixed "hot spot" in the deeper surface of the mantle, the heat source successively supplying magma that formed the volcanoes (Wilson 1963). In 1972, W.J. Morgan (1972a, 1972b) extended Wilson's idea to include the Emperor Seamounts, which, he argued, were a continuation of the Hawaiian Ridge. Considered as a series of islands moving northwest on a plate at 4 cm per year, with the youngest islands constantly replenished from the hot spot, the theory has changed our ideas of the age of the islands, provided new measures of the length of time during which colonization and evolution could have occurred, and stimulated speculation that challenges traditional dispersalist biogeography (Rotondo et al. 1981; Springer 1982).

The physical features and the biota of Hawai'i today are intimately tied to the geological evolution of both the Pacific basin and the islands themselves. From a satellite a few hundred miles above the surface of the earth, the islands appear as mere pinpoints in the the Pacific Ocean, the largest ocean basin in the world. Despite their small size, the islands form a 1,600-mile (2,550-km) arc from 22°N to 19°N, rising from the sea floor more than 30,000 ft (10,000 m) to their highest point, higher even than Mt. Everest. Northwest of Kure, the oldest island in the archipelago, the Emperor Seamounts, a chain of 12 seamounts, lie thousands of feet below the sea surface. Between Kure in the north and Hawaii in the south, a panorama of land forms reflects a history of volcanic action, erosion, subsidence, and reef building. The volcanic characteristics of Kure, Midway, and others of the Northwestern Hawaiian Islands lie beneath thick caps of coral reef; there follow 11 islands that are variously dissected volcanic domes, their coastlines fringed by coral reefs, solution benches, and calcareous sand beaches. Hawai'i, the last island in the chain, is less than 500,000 years old and almost entirely lacks fringing reefs, but two of its volcanoes, Kilauea and Mauna Loa, still spew forth masses of molten lava. Southeast, off the coast of Hawai'i, Loihi, an island as yet unborn, grows 5,000 ft (1,500 m) below the surface of the sea.

In the papers that follow, Clague and Dalrymple describe the Hawaiian Islands in terms of modern geophysical theory; Ladd, Tracey, and Gross provide a description of the most ambitious drilling project ever attempted in Hawaii during which the thick coral cap of Midway was penetrated by drill bit to basalt at a depth of more than 1,200 ft (400 m); Walker reviews the geology and volcanology of the islands; and Loihi, the as yet unborn Hawaiian island, is described from the depths of the sea by Normark, Clague, and Moore.

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

David A. Clague and G. Brent Dalrymple, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025

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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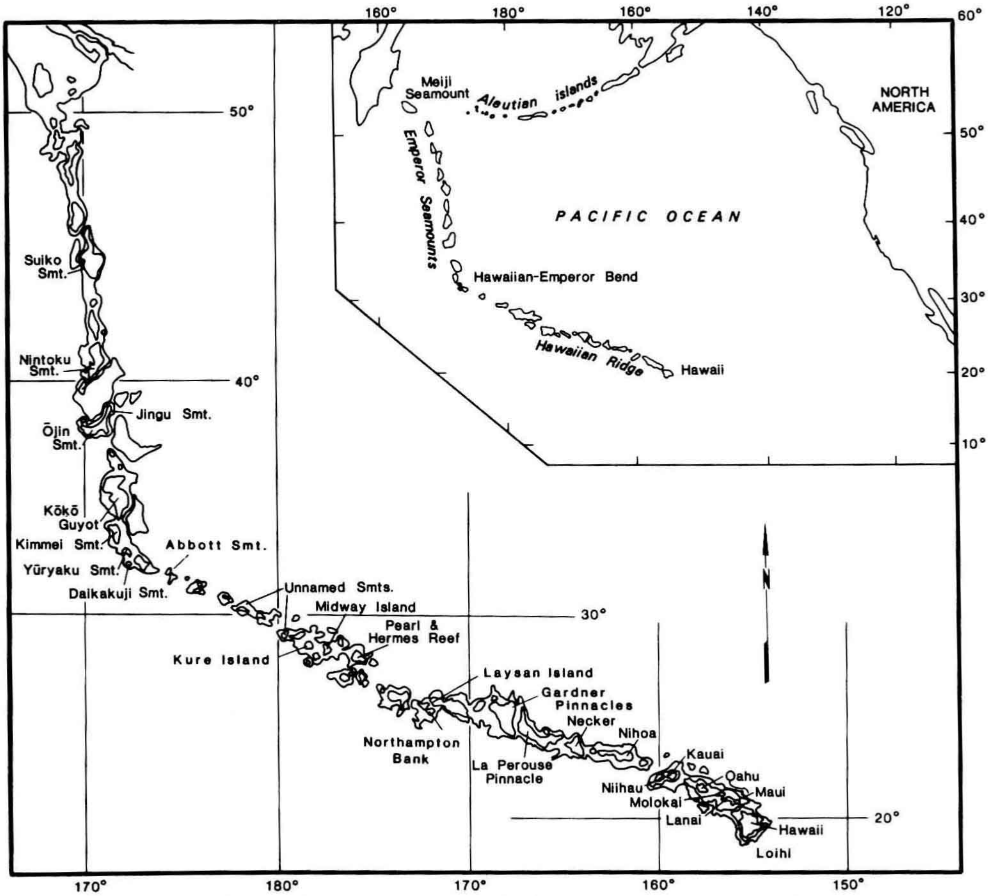

Figure 1. Bathymetry of the Hawaiian Emperor volcanic chain modified from Chase and others (1970). Inset shows the location of the chain in the central north Pacific. Contour interval is 1 km.

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 Jingu 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

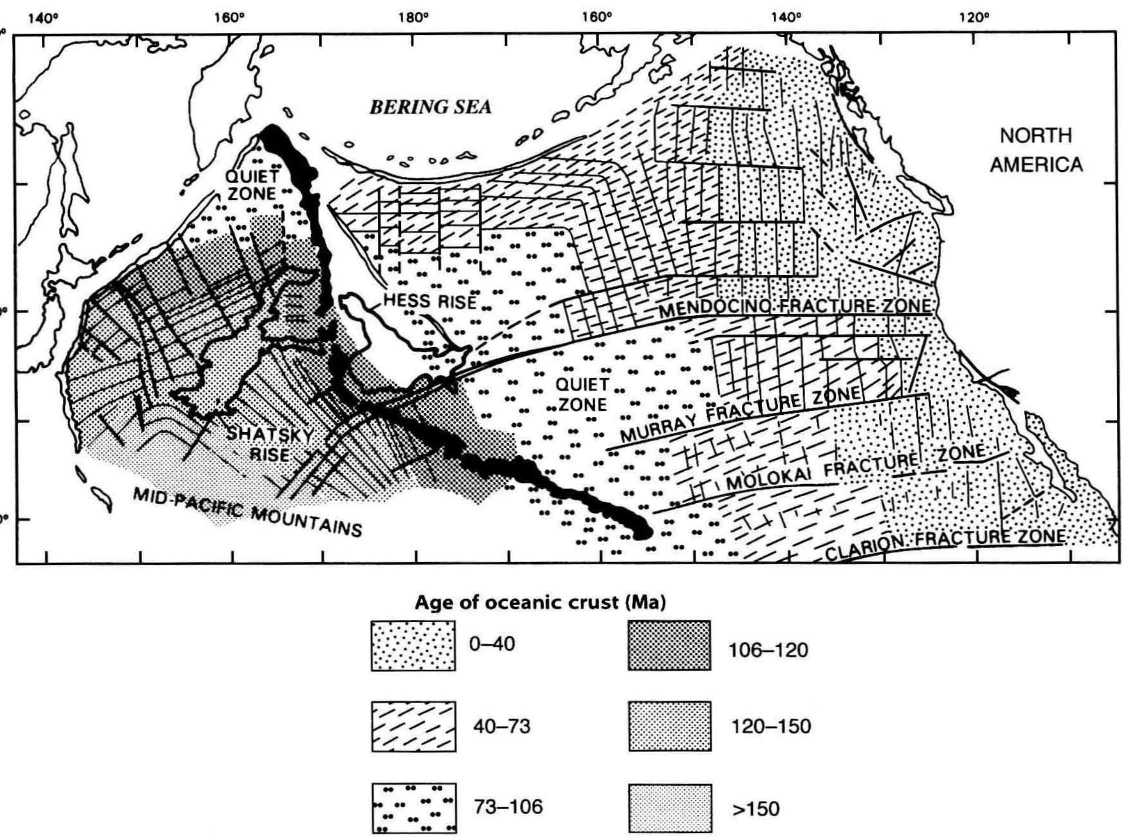

Figure 2. Crustal structure and age map of the north Pacific modified from Hilde and others (1976). The Hawaiian-Emperor chain crosscuts preexisting fracture zones and the Mesozoic magnetic anomaly sequence.

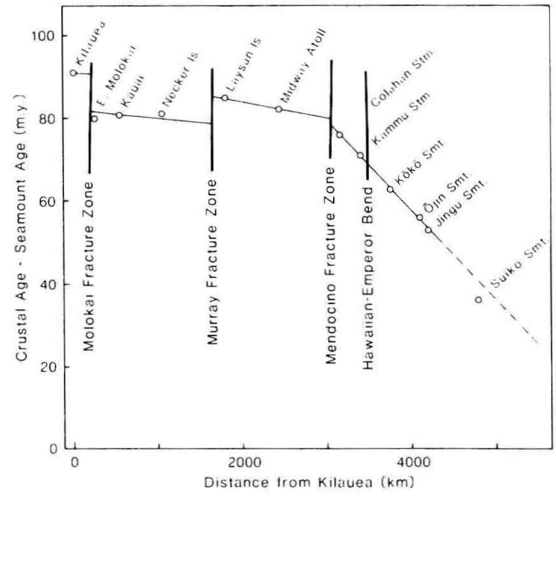

Figure 3. Plot of age of the oceanic crust when each overlying seamount formed as a function of distance from Kilauea. Offsets are at fracture zones. Along the Hawaiian chain both the crust and the volcanoes increase in age to the west so the crustal age when the volcanoes formed is roughly constant. 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