THE HAWAIIAN-EMPEROR VOLCANIC CHAIN
Part I
Geologic Evolution

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

ABSTRACT

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

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

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

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

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

INTRODUCTION

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

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

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

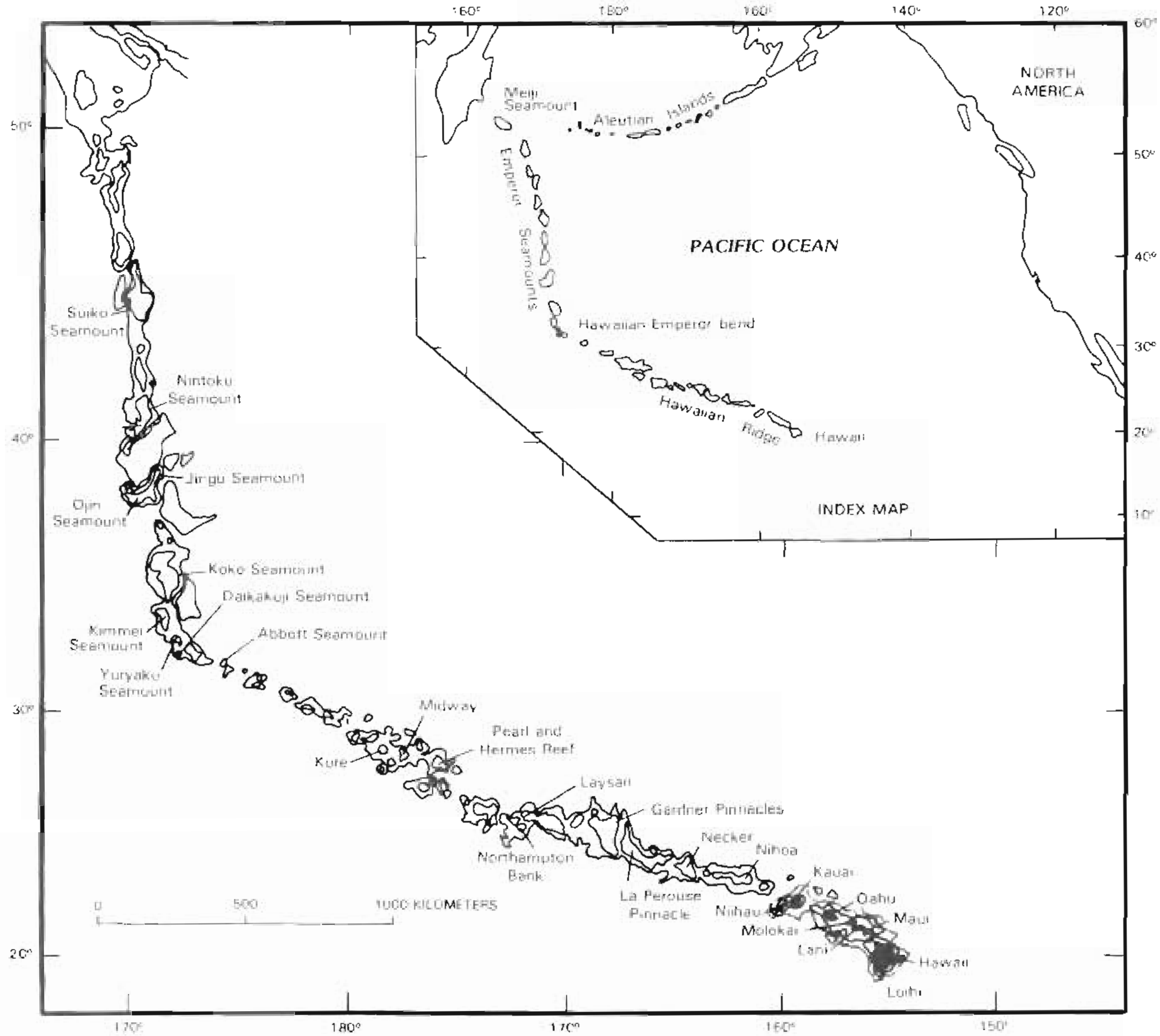

FIGURE 1.1 – Bathymetry of Hawaiian-Emperor volcanic chain modified from Chase and others (1970). Contours at 1-km and 2-km depths shown in area of the chain only. Inset shows location of chain (outlined by 2-km depth contour) in central North Pacific.

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

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

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

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

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STRUCTURE AND AGE OF THE UNDERLYING CRUST

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

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

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

ERUPTIVE SEQUENCE

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

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

GEOLOGIC HISTORY AND EVOLUTION OF GEOLOGIC CONCEPTS, ISLAND OF HAWAII

By Donald W. Peterson *and* Richard B. Moore

ABSTRACT

The Island of Hawaii consists of five Quaternary shield volcanoes: Kohala, Mauna Kea, Hualalai, Mauna Loa, and Kilauea, in order of latest activity. Loihi Seamount, an active volcano 25–30 km south of the island, may eventually grow to merge with the Island of Hawaii.

Early Polynesian settlers on Hawaii kept no written records, and the visits of the earliest European explorers were too brief to contribute much information about the volcanoes. Systematic observations of Hawaiian volcanic activity began in the 1820's, and records by missionaries, explorers, botanists, and geologists described the general characteristics of Hawaiian eruptions and the morphology of the volcanoes. During the 19th century, the geologists J.D. Dana and C.E. Dutton developed basic concepts of Hawaiian volcanic processes that differed considerably from ideas then commonly held about volcanism. The Hawaiian Volcano Observatory, founded in 1912 under the direction of T.A. Jaggar, launched a program of continuous, systematic surveillance of Kilauea and Mauna Loa Volcanoes, which has continued until the present time.

During the first half of the 20th century, understanding of the geologic history of the island advanced by means of frequent observations of eruptions, recognition and study of contrasting rock types, and comprehensive reconnaissance mapping that charted the distribution of rock types and the structure of the volcanoes. More recently, additional understanding has been achieved through geophysical studies, offshore submarine investigations, numerical dating of rocks, advances in petrology and geochemistry, continuous surveillance and monitoring of eruptions, and more detailed geologic mapping.

These continuing advances have permitted earlier concepts on the evolution of Hawaiian volcanoes to be gradually modified, and the order of events, as currently understood, follows this sequence:

1. **Initial stage. Basanite, alkalic basalt, and lava transitional to tholeiite build a moderately steep-sided edifice from the deep ocean floor.**
2. **Shield-building stage. Principal development of shield volcano; eruptions are frequent and voluminous from vents in summit area and along radial rift zones; repeated cycles of caldera formation and filling; weight of growing edifice causes regional subsidence. Three substages: (a) submarine—pillow lavas build moderately sloping submarine edifice; (b) sea-level—vigorous interaction between degassing molten lava and ocean waves, lava-steam explosions, hyaloclastite deposits; (c) subaerial—pahoehoe and aa lava flows build gently sloping shield volcano; processes of substages a and b may continue below and at sea level.**
3. **Capping stage. Alkalic basalt and related differentiated rocks build steeply sloping cap over tholeiitic shield; eruption frequency diminishes, explosive eruptions increase; final caldera buried.**
4. **Erosional stage. Frequency of eruptions declines to zero; stream and wave erosion cuts valleys and cliffs; coral reefs may form offshore.**
5. **Renewed volcanism stage. After long quiescence, highly differentiated lava and tephra erupt intermittently; erosion and reef building continue.**
6. **Atoll stage. Volcano is eroded to sea level abetted by regional subsidence; structure encircled and capped by coral reefs.**
7. **Late seamount stage. Regional subsidence eventually causes edifice to sink below sea level where it quietly remains as a seamount.**

The volcanoes of the Island of Hawaii represent only the first four stages. Loihi is at stage 1 or 2a, Kilauea and Mauna Loa are at 2c, Hualalai and Mauna Kea at 3, and Kohala at 4.

The petrologic history of each Hawaiian volcano is summarized by silica- and magnesia-variation diagrams. These diagrams also illustrate chemical differences and similarities among the volcanoes, the differentiation trends of basaltic magmas, and the major role played by olivine in controlling basalt composition.

Though volcanic activity has dominated the development of the island, other geologic agents have also been at work. Subsidence caused by volcanic loading occurs at a rate of a few millimeters per year. Eustatic changes of sea level, chiefly during the Pleistocene, gave rise to marine terraces, most of which are below the modern strandline. High rainfall on the windward side has caused erosion of deep canyons having thick deposits of sediment in their lower reaches. Pleistocene glacial deposits cap Mauna Kea. Fault scarps are common on the active volcanoes Mauna Loa and Kilauea. Tsunamis generated by local and distant earthquakes have caused coastline erosion and redeposition every few decades through historical time and, by inference, throughout the entire life of the island.

INTRODUCTION

Hawaii, one of the world's largest volcanic islands, lies at the southeastern end of the Hawaiian Ridge, a linear chain of mostly submarine volcanic mountains that extends for 3,500 km through the central Pacific Ocean (fig. 7.1). The eight main Hawaiian islands span about 640 km from southeast to northwest; numerous small islands, atolls, reefs, and shoals lie farther northwest, extending the archipelago proper to about 2,600 km. The exclusively submarine portion of the Hawaiian Ridge continues northwestward for another

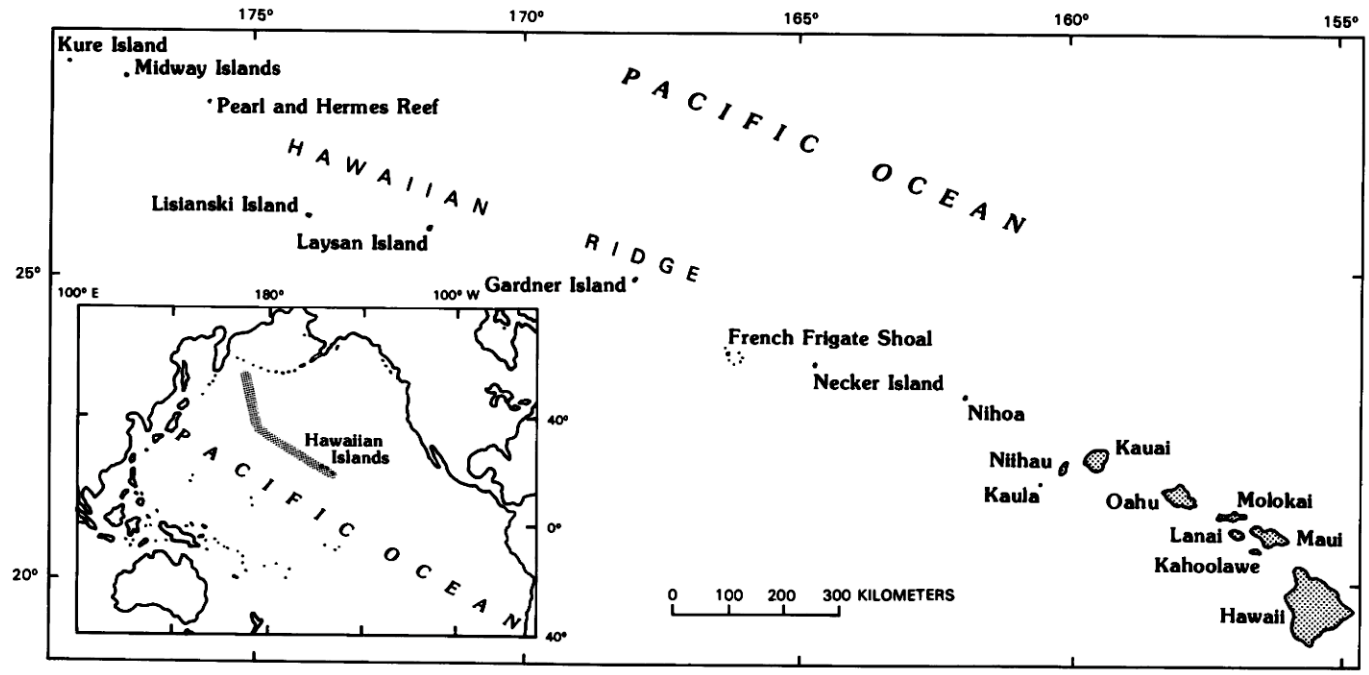

FIGURE 7.1.—Hawaiian archipelago showing location of eight main Hawaiian Islands at southeast end and small islands, atolls, and reefs that extend northwestward along Hawaiian Ridge. Pattern of inset shows location of Hawaiian-Emperor Chain.

900 km, then bends sharply northward to become the Emperor Seamounts, a similar linear chain that extends for another 2,500 km as far as the Aleutian Trench (fig. 7.1). The combined Hawaiian-Emperor volcanic chain is thought to record the persistent movement of the Pacific plate over a stationary melting spot beneath the crust (Dalrymple and others, 1973). The magma generated erupts to build volcanoes at the surface of the plate above the melting spot; as the plate moves on, these volcanoes cease growing but new ones begin. The Island of Hawaii is now thought to lie just north of the melting spot. The origin of the Hawaiian-Emperor Chain is reviewed by Clague and Dalrymple (chapter 1, part I).

Hawaii consists of five individual volcanoes: Kohala, Mauna Kea, Hualalai, Mauna Loa, and Kilauea (fig. 7.2; table 7.1). They rise from the sea floor, which lies here at a depth of about 5–6 km; the island is only their uppermost part, and by far the greatest part of their bulk lies beneath the ocean surface (table 7.2). The subaerial part of each volcano is typically shield shaped, though some have been modified by erosion.

Of the five volcanoes, Kohala, which forms the northernmost part of the island (fig. 7.2), has been inactive the longest. Stream erosion has deeply incised its northeastern flank, though the other flanks are less dissected. Cinder cones stud the upper part of the shield. Kohala last erupted at about 60 ka (McDougall and Swanson, 1972). Adjoining Kohala on the southeast is Mauna Kea, whose summit (4206 m) is the highest point on the island. Cinder cones are abundant on Mauna Kea; its most recent eruptions were at about 3.6 ka (Porter and others, 1979b). Several canyons incise the lower portions of its northeastern flank, whereas the remainder of the volcano has been little affected by erosion.

South of Mauna Kea is Mauna Loa, whose surface accounts for more than half the area of the island (table 7.1). A caldera occupies its summit, several pit craters indent the surface near the summit, and prominent rift zones, consisting of cinder and spatter cones, spatter ramparts, fissures, and small craters, extend northeast and southwest from the summit. Mauna Loa has erupted frequently in historical time, most recently in 1984 (Lockwood and others, chapter 19, 1985), and most of its surface is not eroded. Northwest of Mauna Loa is Hualalai, a relatively steep-sided shield with many cinder cones on its upper parts; it is essentially undissected by erosion. It has erupted once in historical time (1800–1801), from vents along its northwest rift zone. Abutting Mauna Loa's southeast flank is Kilauea, the most readily accessible and best studied of Hawaii's volcanoes. A caldera occupies its summit area, and several large pit craters indent the summit area and upper east rift zone. Rift zones extend from the caldera to beyond the shoreline both east and southwest from the summit. Kilauea, like Mauna Loa, has erupted frequently throughout historical time; the eruptions of these two volcanoes have provided much significant information about processes of basaltic volcanism.

Loihi is a seamount located 30 km south of the south coast of Hawaii (figs. 7.2, 7.8). Its highest point reaches to within about 950 m of the ocean surface. Ongoing studies have revealed evidence of its recent eruptive activity and demonstrate that it is a growing submarine volcano (Malahoff, chapter 6; Malahoff and others, 1982; Moore and others, 1982).

The geologic history of a basaltic volcanic island superficially may appear to be quite simple—a long sequence of repeated lava flows has constructed a broad, layered volcanic edifice. The wide

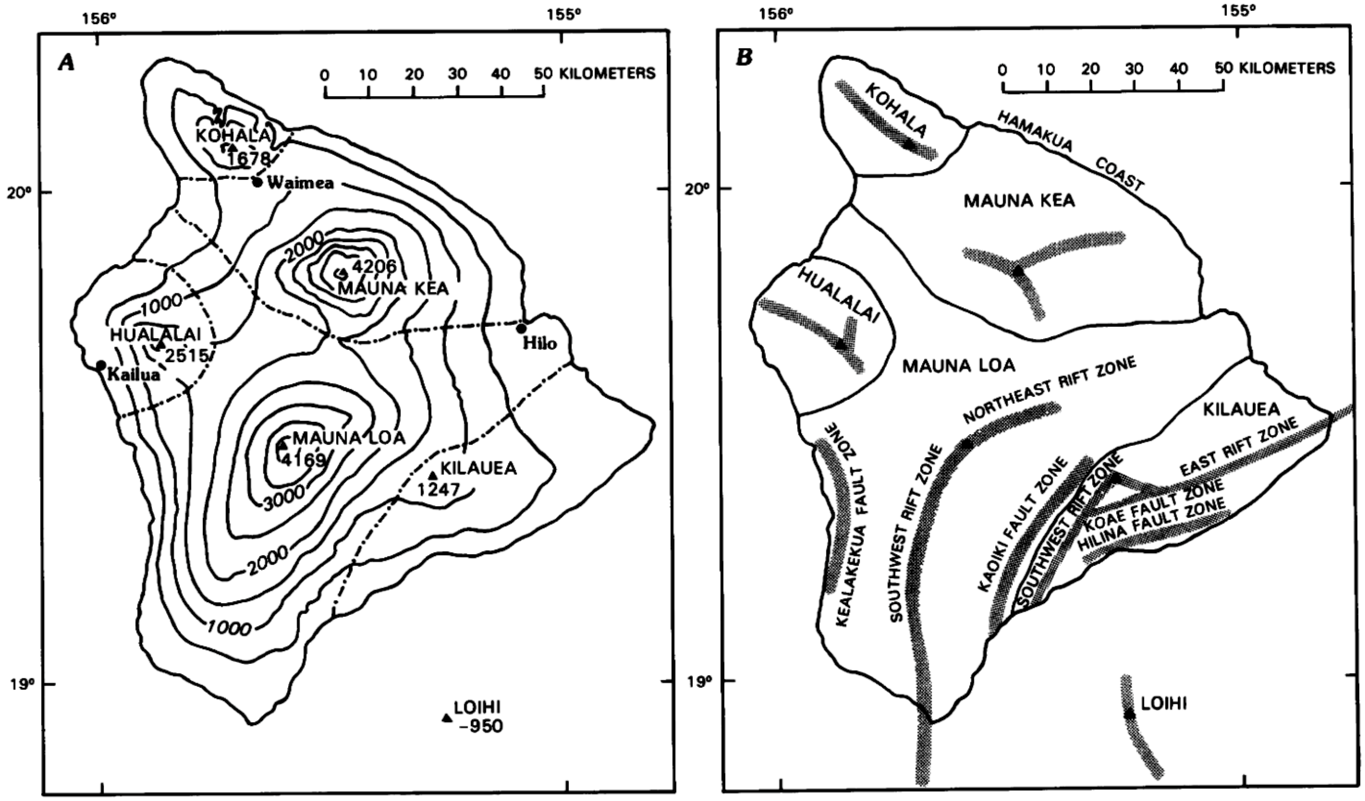

FIGURE 7.2.—Island of Hawaii and Loihi Seamount showing major geographic and geologic features. ***A***, Generalized topography and boundaries of five volcanoes. Contours and summit elevations in meters. ***B***, Major rift zones and fault zones; those on Kilauea and Mauna Loa are named.

TABLE 7.1.—*Physical dimensions of the subaerial portions of Hawaii's volcanoes*

[Adapted from Stearns and Macdonald, 1946, p. 24]

Volcano	Elevation of highest point (m)	Area (km^2)	Percent of area of island
Mauna Loa	4,169	5,271	50.5
Kilauea	1,247	1,430	13.7
Hualalai	2,521	751	7.2
Mauna Kea	4,206	2,380	22.8
Kohala	1,670	606	5.8
Entire island	4,206	10,438	100

TABLE 7.2.—*Volume and relative percentages of subaerial and submarine mass of each volcano and for entire Island of Hawaii*

[Volumetric data from Bargar and Jackson, 1974, table 1; sea floor assumed approximately level at depth of 5 km below sea level]

	Subaerial part		Submarine part		Total	
Volcano	Volume above sea level (10^3 km)	Fraction above sea level (percent)	Volume below sea level (10^3 km)	Fraction below sea level (percent)	Volume above plus below sea level (10^3 km)	Fraction of entire island mass (percent)
Mauna Loa	7.5	17.6	35.0	82.4	42.5	38
Kilauea	0.7	3.6	18.7	96.4	19.4	17
Hualalai	0.6	4.8	11.8	95.2	12.4	11
Mauna Kea	3.1	12.5	21.7	87.5	24.8	22
Kohala	0.4	2.9	13.6	97.1	14.0	12
Entire Island	12.3	10.9	100.8	89.1	113.1	100

variety of subjects covered by the succeeding papers in this section, however, demonstrates that such a view is oversimplified, and the geologic history actually includes a rich diversity of processes and events that were deciphered through the efforts of a long succession of geologists and other workers. Hence the geologic history of the Island of Hawaii will here be related from the point of view of how the concepts evolved during the last two centuries—in essence, a history of the development of the understanding of Hawaii's geologic history.

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