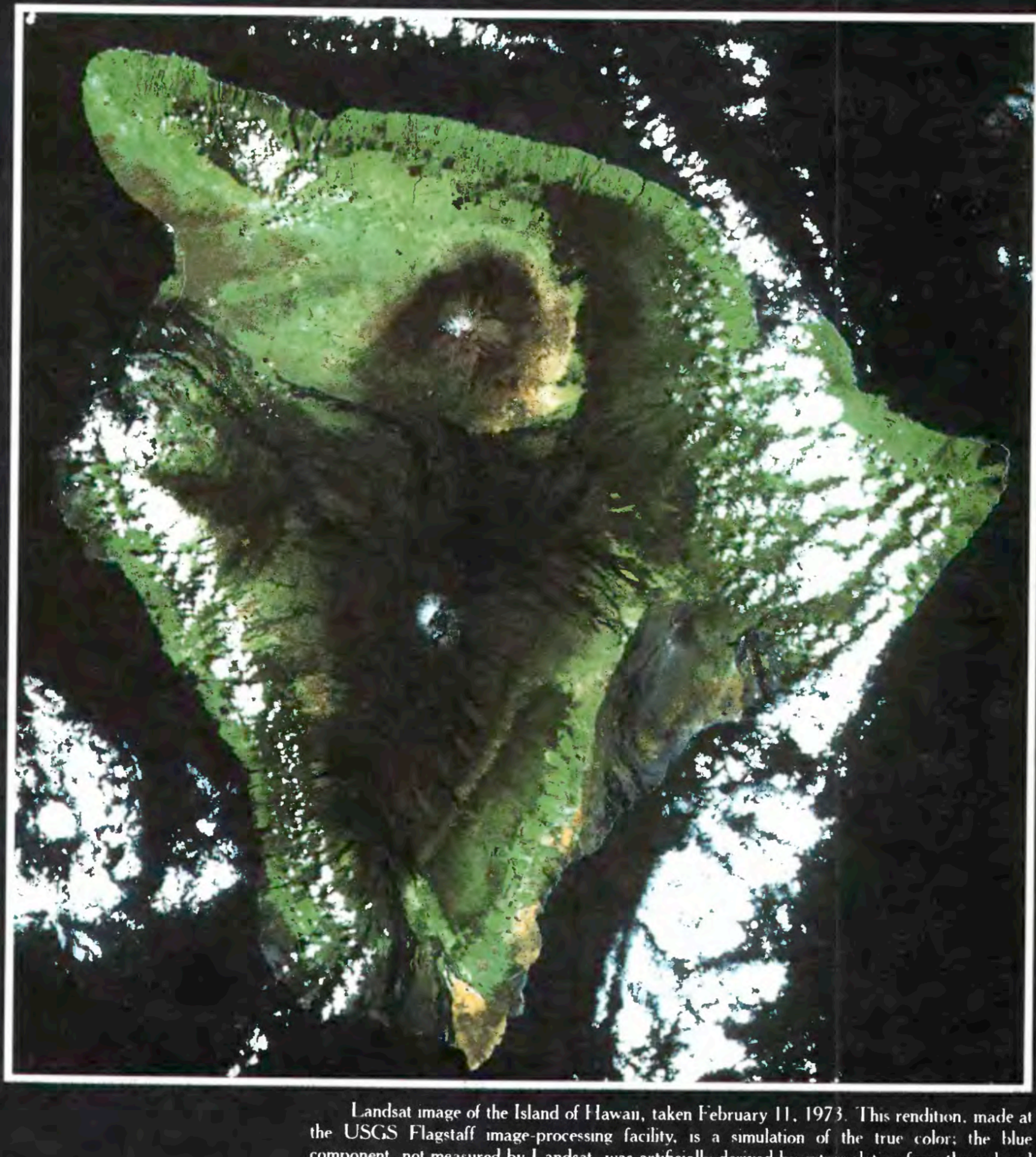

Landsat image of the Island of Hawaii, taken February 11, 1973. This rendition, made at the USGS Flagstaff image-processing facility, is a simulation of the true color; the blue component, not measured by Landsat, was artificially derived by extrapolation from the red and green channels. Clearly visible in lower center are lava flows from the southwest and northeast rift zones of Mauna Loa Volcano, radiating from its summit caldera.

Man with Paddle
Hawaiian Petroglyph
Puna, Hawaii

GEOLOGY OF THE ISLAND OF HAWAII

The Island of Hawaii, aptly termed the "Big Island," is the setting for all current and most historical volcanic activity in the Hawaiian Chain, and the work of the Hawaiian Volcano Observatory has of necessity been concerned largely with the active volcanoes. Modern volcanism can only be understood, however, through study of past volcanic activity. Accordingly, many workers at HVO have participated in mapping projects that extend our knowledge of Hawaiian volcanic history at least back to the emergence of the volcanoes above sea level.

The latest geologic map of the Island of Hawaii was published by Harold Stearns and Gordon Macdonald in 1946 as part of a series of maps and descriptive bulletins for all the Hawaiian Islands. A revision of that map currently being prepared by a consortium of USGS and university geologists will incorporate information from a number of chapters in this section.

The section begins with a broad view of where we are now and where we have been in our understanding of the geology of Hawaii. With modern satellites we no longer have to confine ourselves to earthbound observation—chapter 8 gives us a view from space. Chapters 9 and 10 treat radiocarbon dating, a technique that has been essential in unraveling the prehistoric record of Hawaiian volcanism. Kilauea is the most active Hawaiian volcano in recent times, and chapters 11 through 17 discuss its activity from the most recent to the most ancient. Two following chapters on Mauna Loa provide comparable insight into both the historical and prehistoric behavior of that largest volcano in the Hawaiian Chain. The third volcano on the Big Island that can be considered active is Hualalai; chapter 20 provides the first modern assessment of its geologic history. Mauna Kea, dormant for about 4,000 years, underwent Pleistocene glaciation as well as volcanic activity—the relation between the two is discussed in chapter 21.

The section concludes with a revised assessment of volcanic hazards in the Hawaiian Islands; such hazards are mostly associated with the active volcanoes on the Island of Hawaii. Revised hazard-zone maps should be of value to all concerned with use of the precious and fragile land resources on the Big Island.

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

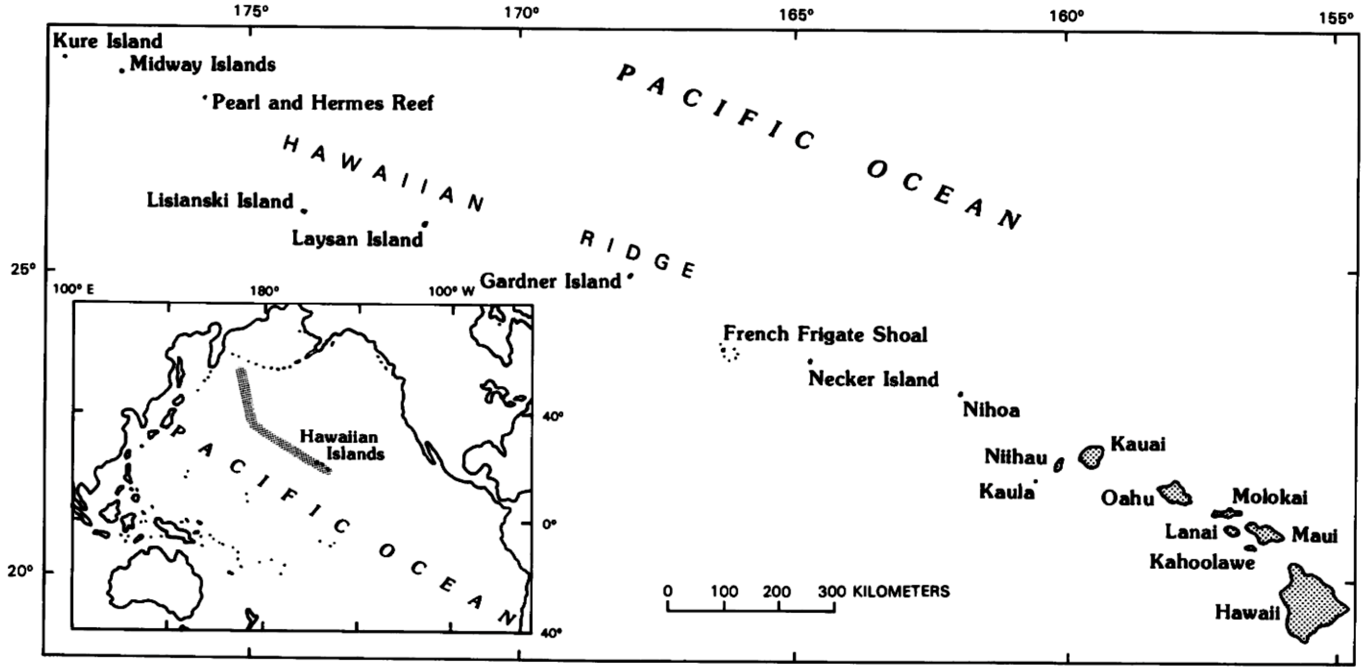

FIGURE 7.1.—Hawaiian archipelago showing location of eight main Hawaiian Islands at southeast end and small islands, atolls, and reefs that extend northwestward along Hawaiian Ridge. Pattern of inset shows location of Hawaiian-Emperor Chain.

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

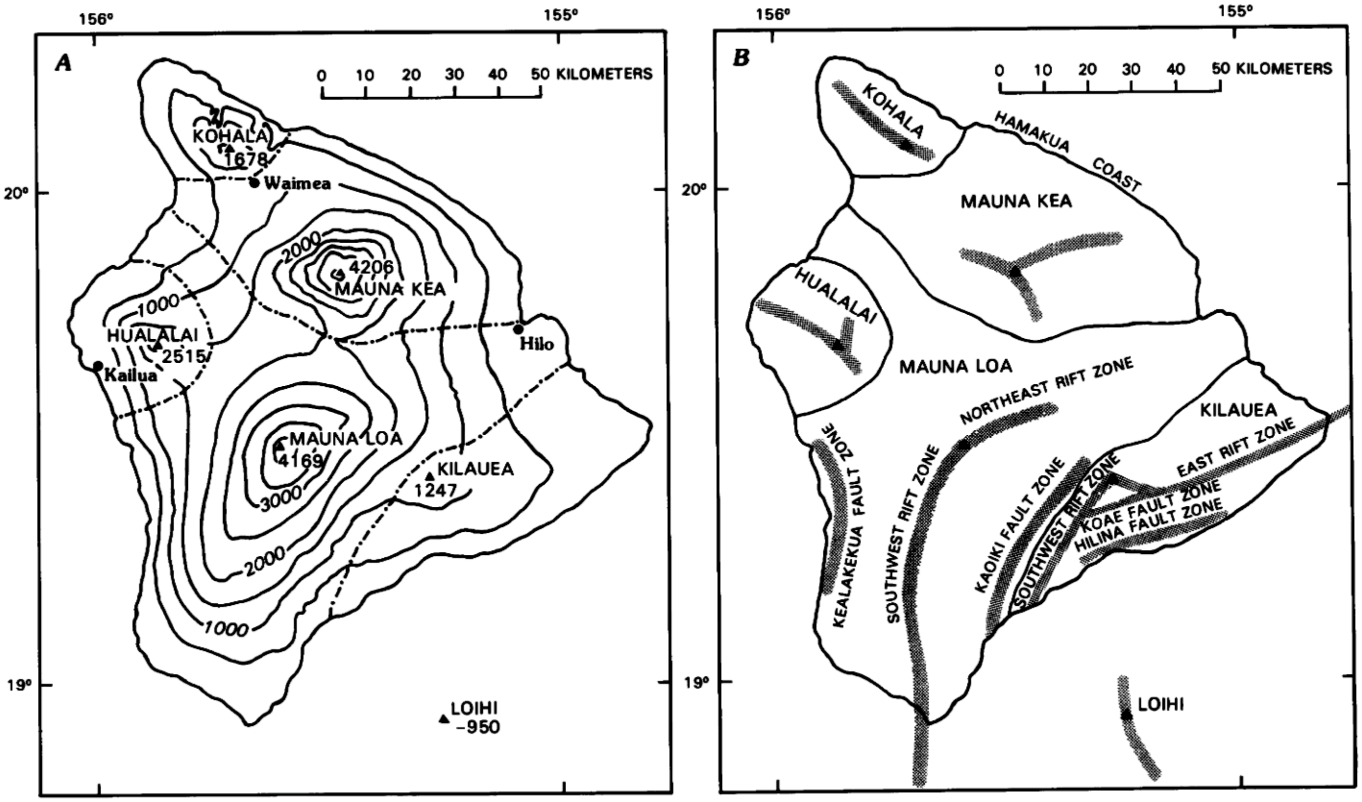

FIGURE 7.2.—Island of Hawaii and Loihi Seamount showing major geographic and geologic features. ***A***, Generalized topography and boundaries of five volcanoes. Contours and summit elevations in meters. ***B***, Major rift zones and fault zones; those on Kilauea and Mauna Loa are named.

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

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.

ACKNOWLEDGMENTS

Ideas summarized in this paper stem from the long progression of geologists who have worked on Hawaii, far too numerous to mention individually, but who merit sincere gratitude and are here collectively recognized. Special thanks are given to R.W. Decker, who stimulated the production of the paper, and to R.T. Holcomb, who served as a ready source of information, ideas, and constructive criticism. We also particularly thank R.I. Tilling and W. A. Duffield, who greatly improved the paper by their incisive and thorough reviews.

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]

Volcano	Subaerial part		Submarine part		Total	
	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

DEVELOPMENT OF CONCEPTS OF THE GEOLOGIC HISTORY OF HAWAII

PROGRESS FROM THE LATE 18TH CENTURY TO THE MID-20TH CENTURY

It is possible to summarize simplistically the geologic history of Hawaii in a single sentence: Hawaii has been built of adjacent and partly overlapping mounds of basaltic lava flows and small amounts of tephra, which originated on the ocean floor and successively grew above the sea to form the five distinct volcanoes that compose the still-evolving island. However, such a condensed history does not consider related processes and conditions that have shaped these volcanoes, such as changes in composition of the magma, shifts in vent location, causes and manifestations of stresses within the volcanoes, diversity of eruptive style and flow behavior, variations in duration of inactive intervals, and interactions between eruptive products and sea water. Underlying the development of the island, however, is the fundamental process of volcanism, for without countless and repeated volcanic eruptions, the Island of Hawaii would not exist.

Evidence of recent volcanism was noticed by even the earliest European visitors. The journals of Captain James Cook, who was the first European to visit Hawaii in 1778, emphasized navigation, geographic discovery, flora, fauna, and the nature of the endemic people, noted the volcanic characteristics of the island (Beaglehole, 1967, p. 486): "The coast of the Kau district presents a prospect of the most horrid and dreary kind: the whole country appearing to have undergone a dreadful convulsion. The ground is covered with cinders and intersected with black streaks which mark the course of lava that has flowed, not many ages back, from the mountain to the sea. The southern promontory looks like the dregs of a volcano." One of Cook's sailors, John Ledyard, led a field party to the interior of the island, where fresh lava flows and other signs of recent volcanic activity were encountered. Ledyard (1783) expressed the astute opinion that the entire island was of volcanic origin. However, members of the Cook expedition seemed unaware that the island included active volcanoes. Captain George Vancouver, on an expedition to Hawaii in 1793–94, was the first to record volcanic activity on the island (Vancouver, 1798, p. 8). Archibald Menzies, the botanist on the Vancouver expedition, explored part of the interior of the island and led ascents of Hualalai and Mauna Loa. Menzies' account of this first recorded ascent of Mauna Loa is a fascinating tale of hardship and persistence (see Hitchcock, 1909, p. 63–79). Menzies described the volcanic character of Mauna Loa, particularly the summit region, and he noted fume clouds and ash issuing from Kilauea.

The first detailed descriptions of Hawaiian volcanic activity were written by missionaries and were based in particular on a notable trip around the island trip in 1823. William Ellis (1827) described the characteristics of rocks and landforms and provided sketches and vivid impressions of the vigorous behavior of lava lakes and vents on the floor of Kilauea caldera. Joseph Goodrich (1826), an American missionary stationed at Hilo, wrote to Benjamin Silliman, editor of the American Journal of Science, with information about Kilauea; his earliest letter recounted the same journey described by Ellis. Based on the volcanic activity and the landforms they observed throughout the trip, these missionaries ascribed the origin of the entire island to volcanism. Ellis summarized this conclusion as follows (Ellis, 1827, p. 181): "The whole island of Hawaii, covering a space of four thousand square miles, from the summits of its lofty mountains * * * down to the beach, is, according to every observation we could make, one complete mass of lava, or other volcanic matter, in different stages of decomposition. Perforated with innumerable apertures in the shape of craters, the island forms a hollow cone over one vast furnace, situated in the heart of a stupendous submarine mountain, rising from the bottom of the sea * * *."

During the following years, sporadic visits to the volcanoes were reported by missionaries, sea captains, and a few other persons. The accounts of most of these visits are conveniently summarized by Dana (1890), Brigham (1909), and Hitchcock (1909). The accounts of several missionaries of this period, notably Goodrich and C.S. Stewart, were published in the American Journal of Science, the Missionary Herald, and a few other journals (see Macdonald, 1947). The botanist David Douglas described his visits to Kilauea and Mauna Loa in 1834 (Douglas, 1914; Harvey, 1947, p. 220-231). These accounts document the major changes in the morphology of Kilauea caldera and the persistent action of the lava lake and other vents on the caldera floor during the early and middle decades of the nineteenth century.

The first systematic exploration of the Hawaiian volcanoes was carried out by members of the Wilkes expedition during 1840–41. Wilkes' (1845) own narrative includes fascinating accounts of the exploration and of specific trips to the volcanoes, but J.D. Dana (1849) provided geological insight into the volcanoes and their role in the development of the island (Appleman, chapter 60). Dana noted the generally quiet behavior of Hawaiian volcanoes, their gently sloping flanks, and the scarcity of products from explosive eruptions. He correctly ascribed these features to the high fluidity of the Hawaiian lava in contrast to the more viscous lava of steeper sided volcanoes with more explosive habits. He also described the concentration of vents in the summit areas and along narrow linear zones radiating from the summits (the concept of the rift zone), and he correlated flank eruptions of Kilauea with concurrent subsidence of the lava lake and caldera floor—evidence of possible connection between flank and summit magma conduits. Even so, Dana regarded Kilauea as only a vent of Mauna Loa, rather than an independent volcano. For example, he described the island of Hawaii as being made up of three volcanoes, "Mount" Kea, "Mount" Loa, and Hualalai (Dana, 1849, p. 159), and he stated that volcanic activity was "confined to Loa and Hualalai" (p. 168). Furthermore, he included his general discussion of Kilauea (p. 171–206) in the section on Mauna Loa (p. 168–214). Nevertheless, he wondered about the lack of correlation in their activity and was puzzled that lava could be elevated to erupt at the summit of Mauna Loa while nearly 10,000 feet lower an open, constantly active conduit fed the lava lake at Kilauea. Although he proposed a separation of conduits (p. 218–221), he did not suggest that Kilauea might be an independent volcano. Finally, he described Kohala as a ridge separated from Mauna Kea by a scarp, but he did not define it as a separate volcano or even as part of the three volcanoes making up the island.

The eruptive activity of Kilauea and Mauna Loa during the next four decades (1840–1880) was reasonably well documented, in spite of only irregular visits and the lack of an established system of surveillance. This documentation is chiefly owing to Titus Coan, a missionary stationed at Hilo and a perceptive and dedicated volcano observer. His missionary duties required frequent trips past Kilauea, and from 1840 to the early 1880's he recorded the volcano's activity. From the 1850's he summarized his observations in letters to his friend, J.D. Dana, who became the editor of the American Journal of Science, and Coan's graphic descriptions regularly found their way into the pages of that journal. He also observed the activity of Mauna Loa, although access there was much more difficult; he recorded the dates of eruption, and for most of the significant ones was able to visit the scene of the action. Several other missionaries, a few scientists, and an occasional tourist also made observations that were published. These reports were compiled by Dana (1890), Hitchcock (1909), Brigham (1909), and Macdonald (1947). Nearly all accounts from those of the Wilkes expedition to Dutton's study in 1882 were purely descriptive, but the record they chronicled provided evidence supporting the concept that the long-term growth of the island was the product of episodic lava flows from the active volcanoes.

C.E. Dutton carried out the most extensive geologic studies of Hawaii in the 19th century (Dutton, 1884). He described the surface morphology and structure of the five volcanoes. He recognized that Kilauea is a separate volcano, distinct from Mauna Loa (Dutton, 1884, p. 120–121) for the following reasons: (1) The distance between Kilauea and Mauna Loa is about the same as the distance between other pairs of adjacent volcanoes of the island; (2) according to hydrostatic principles, the difference in elevation between lava lakes at Kilauea and the summit of Mauna Loa is too great to permit liquid continuity; (3) Kilauea caldera "is situated on a totally distinct mountain pile," the top of which stands topographically above a saddle that separates the two volcanoes. Dutton observed that flows from the two volcanoes are intercalated and thus that the two volcanoes are intergrown. He concurred with Dana that Hawaiian volcanoes have gentler flanks than many other well-known volcanoes. Dutton emphasized the immense size of Mauna Loa, especially in view of its apparently huge submarine part, and he reasoned that Mauna Kea, which rises higher than Mauna Loa but has steeper sides and a smaller base, is considerably smaller in volume.

The distinction between the basaltic lava types of pahoehoe and aa commonly is credited to Dutton (1884 cited by Macdonald, 1972, p. 71; Peterson and Tilling, 1980, p. 272), although Dana (1849, p. 161–163) accurately described "pahoihoi" and "clinkers" several decades earlier. However, Dutton (1884, p. 95) apparently first introduced the Hawaiian term aa for the slaggy, rough, clinkery type. After Dutton's report, the terms aa and pahoehoe came into common use. Dutton (1884) suggested that the two lava types form because of contrasts in the dimensions of the lava flows and in the relations among lava movement, cooling, and solidification. He also (p. 105) proposed that the term caldera is more appropriate than the term crater to describe the large depressions at the summits of Kilauea and Mauna Loa.

During the 19th century, Kilauea's intracaldera lava lake, which was active for many decades, received the most attention. Dutton described his own observations and quoted extensively from the writings of others in summarizing activity that included vigorous fountaining and lava flows, quiet circulation within multiple lava lakes, updoming of portions of the caldera floor, and noisy and sometimes spattering "blowing cones," all of which were interspersed with major episodes of lava withdrawal and partial collapse of the solid floor of the caldera (Dutton, 1884, p. 106–119). Such behavior led him to speculate (p. 126) that the caldera formed as a consequence of repeated fluctuations in the height of the lava column. He reasoned that when the column was high, wall rocks were softened or melted by magmatic heat, and when the column lowered, such weakened rock spalled off and sank; thus repeated oscillations of the lava-column height caused the depression to enlarge. He seems to have visualized a magma column nearly as wide as the caldera. While not every facet of his explanation finds favor today, Dutton deserves credit for recognizing the process of collapse as essential to the development of the caldera. Like Dana, he recognized that linear zones of weakness (now called rift zones) radiate from the summit and noted that eruptions along these zones were accompanied by lowering of the lava column in the caldera.

Dutton (1884) visited the source of the 1880–81 eruption of lava from the northeast flank of Mauna Loa, and he accurately described the structure and character of the rift zone there. He was impressed by the large volume of lava produced during this 11-month-long eruption and by the small proportion that remained near the vents. He identified vent areas of earlier eruptions and thus gained considerable insight into the manner in which the volcano, and indeed the island, grew from rift eruptions. A brief excerpt is appropriate to summarize the concept he visualized (Dutton, 1884, p. 134–135):

> There is a strange fascination in wandering over this vast expanse of desolation. No doubt the dominant idea is the immensity of it. The best conception of the magnitude of Mauna Loa is to be obtained by attempting to traverse any limited district of it on foot. Mile after mile may be traversed but the landscape seems ever the same. All the great landmarks seem to stand just where they stood an hour before * * *. The only alternations are from aa to pahoehoe. Traces of recent eruptions are seen everywhere, but all the views are fragmentary. So extensive has each and every one of them been that the greater portions of them always reach far beyond the limits of vision, and mingling together are lost in the confusion of multitude. The imagination is discouraged at the thought that this colossal pile has been built up by thousands upon thousands of these eruptions.

Dutton himself saw no eruption in Mokuaweoweo, the summit caldera of Mauna Loa. However, from his review of the observations of others, he concluded that activity at the summit generally preceded flank eruptions and that summit activity declined and ended when lava broke out on the flanks, suggesting hydraulic connections among various vents of the volcano. As he had for the caldera of Kilauea, Dutton advocated for Mokuaweoweo an origin by collapse, citing a lack of evidence for explosive origin and the abundance of partly subsided blocks. He speculated that a caldera would tend to develop at the summit of a volcano when it grew large enough for flank eruptions to occur and draw lava from a summit magma reservoir, thus reducing support beneath the central orifice. He therefore proposed that summit depressions could have existed at both Mauna Loa and Kilauea throughout much of their development (Dutton, 1884, p. 142–143).

Dutton concluded that Mauna Kea had long been inactive, because the rocks are deeply weathered, soil cover is common, and ravines and canyons disrupt the profile of the flanks, particularly on the northeastern, windward side (Dutton, 1884, p. 160, 168–170). He described the abundant cinder cones in the summit area of Mauna Kea and took note of the nearby flows of unusually hard and flinty lava that was used by Hawaiians for tools and weapons (p. 163–164). In recent years these distinctive rocks have been recognized as products of magmatic differentiation, but the idea of differentiation was spawned long after Dutton's time and he did not speculate on the cause of the somewhat unusual character of the quarried rock.

Dutton mentioned Kohala only briefly, recognizing it as the volcano longest inactive on the island, as demonstrated by its deeply incised canyons and its thick soil (Dutton, 1884, p. 171). He described Kohala lava as basalt with a tendency toward andesite, and he noted its many cinder cones. Similarly, his description of Hualalai is brief; he noted the abundant cinder cones in its summit region, the basaltic character of its lava, and the common occurrence of olivine (p. 173–174). He stated (p. 83) that Hualalai erupted three times in the early 19th century, later giving dates of 1801 (p. 181) and of 1805 and 1811 (p. 173), but he did not cite a source for these dates, which are in part at variance with the now commonly accepted time of eruption during 1800–1801 (Moore and others, chapter 20; Ellis, 1827, p. 38; Stearns and Macdonald, 1946, p. 146).

Stimulated by his participation in the Wilkes expedition, Professor James Dwight Dana of Yale University maintained a lively interest in Hawaii throughout his long and distinguished career. He kept himself informed about virtually every reliable observation of activity at Kilauea and Mauna Loa and published many accounts of it in the American Journal of Science. Dana made his second journey to the islands in 1887 at the age of 74 and later published a book (Dana, 1890) that served for years as the definitive work on Hawaiian volcanoes. Dana's general ideas on the geologic history of the volcanoes remained similar to those he developed on the Wilkes expedition, which were summarized above. However, he ultimately accepted the evidence offered by Dutton and others that Kilauea is a separate volcano and not part of Mauna Loa. This change in opinion was evidently not easy for him, as in the process of acquiescing he devoted several pages (Dana, 1890, p. 258–264) to recounting the virtues of his original views.

About two decades later, two major volumes were published about the volcanoes of Hawaii (Brigham, 1909; Hitchcock, 1909); each includes a chronological narrative of the activity of Kilauea and Mauna Loa, and each includes many photographs of volcanic features, as well as maps that illustrate the changes in caldera morphology through the years. Brigham's work also contains many of his own personal observations and experiences. Hitchcock's personal observations are fewer, but he was particularly diligent in documenting information, and the usefulness of his volume is enhanced because of extensive quotations from sources now hard to find. Although neither author developed new concepts on volcano development, their descriptive chronologies are very valuable. The timing of their publication was serendipitous, as these unique reference volumes appeared just before the establishment of the Hawaiian Volcano Observatory (HVO) in January 1912.

The founding of the HVO by T.A. Jaggar began the modern era of continuous surveillance and systematic documentation of the Hawaiian volcanoes (Apple, chapter 61). Jaggar and other HVO staff members made detailed daily observations of Halemaumau, and various scientific instruments were introduced to complement the regular program of observation. The easily accessible lava lake at Halemaumau offered abundant opportunities for observation and experimentation, and Jaggar collaborated with visiting scientists to build a new understanding of the behavior of Hawaiian volcanoes. Vast amounts of data were collected on the circulation and the rise and fall of the lava lake, composition of lava, character of seismicity, ground deformation, gas chemistry, and lava temperatures. In addition to the activities of the lava lake, all eruptions of Mauna Loa and Kilauea were thoroughly documented. Jaggar made several successful long-range forecasts of Mauna Loa activity.

Jaggar was a geologist and a geophysicist; he was a keen observer of eruptive phenomena, and he was much interested in experimentation and development of instruments. He and his collaborators led volcanology from a science of description to a science of quantitative measurement, experimentation, and interpretation. He wrote prolifically (see, for example, Jaggar, 1947); a convenient summary of his major writings appears in Macdonald (1947, p. 83–103).

Jaggar proposed that the magma column of Halemaumau consists of (1) hypomagma, a homogeneous, aphyric fluid from a source deep within the Earth, with gas contained in solution; (2) pyromagma, a vesiculating gas-rich foam, which constitutes the highly fluid portion of lava lakes and includes the lava of erupting fountains and; (3) epimagma, which he also called bench magma, a highly crystalline, pasty, largely degassed but still-incandescent lava forming the floor and lining of lava lakes; he visualized epimagma as forming the contact sheath of the magma conduit. Although Jaggar's terms are chiefly applicable to active lava lakes and have been but little used, they help to illustrate his key concept that the rate and amount of gas vesiculation determine the behavior of erupting lava.

Jaggar postulated a tidal influence on the behavior of Halemaumau lava lake, which led him to propose that activity peaked at solar equinoxes and solstices. Subsequent workers have found little evidence to substantiate the latter proposal, although investigations continue into the possibility that tidal maxima serve as a trigger for some eruptions (Shimozuru, chapter 49; Dzurisin, 1980). Jaggar sought diligently for evidence of cyclicity in eruptive behavior, and he was convinced that changes in behavior were governed by the 11.1-yr sunspot cycle, upon which was superimposed a 134-year cycle defined by the interval between the explosive eruptions of Kilauea in 1790 and 1924. Reexamination of his evidence and the timing of subsequent eruptions have failed to support his concepts regarding the sunspot cycle.

He was impressed by certain coincidences of eruptive events at Mauna Loa and Kilauea; although they rarely erupted simultaneously, Jaggar thought he recognized lowering of the Halemaumau lava lake during eruptions of Mauna Loa. Hence he advocated the view that Kilauea and Mauna Loa are closely interconnected (Jaggar, 1947, p. 90, 200), even though he clearly regarded them as independent systems. He interpreted the island to be arranged as a cross (Jaggar, 1920, p. 193–195; 1947, p. 90), in which the north-northeast-trending upright extends from Mauna Kea summit through the summit and along the southwest rift zone of Mauna Loa to South Point. The transverse arm of the cross extends between Hualalai and Kilauea summits, which are symmetrical about the upright, and the summit of Mauna Loa lies near the intersection of the two elements. Kohala is not part of this structure. (This cross pattern can be recognized by noting the geographical relations of the four volcanoes, see fig. 7.2). The supposed geographic symmetry of Hualalai and Kilauea, the record of occasional explosive eruptions of Kilauea, and Kilauea's lesser output of lava than Mauna Loa convinced Jaggar that Kilauea is older than Mauna Loa and that it is approaching the same state of "decadence" as Hualalai has achieved (Jaggar, 1920, p. 191–198).

Stearns and Macdonald (1946, p. 135) demonstrated that Kilauea and Hualalai behave quite independently of one another. Kilauea's many eruptions since the 1950's, as well as petrogenetic considerations developed after Jaggar's time and discussed later herein, refute any suggestion that the volcano is in late decline. Even though not all of Jaggar's hypotheses have withstood the test of time, his contributions remain monumental. His many observations and thorough documentation of the activity of Kilauea and Mauna Loa constitute a permanent record of the growth processes of Hawaiian volcanoes.

Other scientists made many contributions in studies of Hawaiian volcanism during the decades of the 1910's to 1940's. The petrologic studies of Daly (1911, 1914, 1933, 1944), Cross (1915), and Washington (1923a, b, c) demonstrated the near-constant composition of highly fluid lava throughout most of the subaerial growth of the volcanoes and the variable composition of the late differentiated lava. Through integrated field and laboratory studies, Sidney Powers (1916, 1920) helped document the relations between lava composition and eruptive behavior. Stone (1926) reviewed published reports of Kilauea and was perhaps the first to describe the geology and geologic history of the whole of Kilauea. H.A. Powers (1935) evaluated the differentiation processes and pointed out that crystal fractionation alone could not account for Hawaiian differentiated rocks. Wentworth (1938) examined geomorphic processes and the products of explosive eruptions. Harold T. Stearns and colleagues began systematic geologic mapping in the 1920's, which led to the first geologic map of a part of the island (Stearns and Clark, 1930) and eventually to a comprehensive geologic report about the entire island (Stearns and Macdonald, 1946). Their geologic map of the island (scale 1:125,000) established a consistent stratigraphic nomenclature and thus provided a basis for examining the stratigraphic relations among the five volcanoes (figs. 7.3 and 7.4). The mapping was complemented by petrologic and petrographic studies (Macdonald, 1949a, b). The combined results are the foundation upon which all further geologic investigations of Hawaii have been built.

From his studies throughout the islands, Stearns (1940) defined a progression of four stages of volcanism, which he later (1946, p. 17–20; 1966) expanded to a series of eight stages that describe the growth, erosion, submergence, reef development and posterosion volcanism of the Hawaiian and other islands of the central Pacific (fig. 7.5). The following summary reviews Stearns' ideas as expressed in 1946; their subsequent modifications are discussed later.

Stage 1 involves building the volcano from the ocean floor to sea level. The volcano produces mostly pillow lava, and Stearns believed then that the submarine deposits include extensive tuff from explosive interaction between molten lava and seawater. The first material to emerge above sea level is poorly consolidated ash that erodes rapidly. Eventually subaerial lava flows veneer this material, reducing the rate of wave erosion.

Stage 2 is the subaerial growth of the volcano. Countless thin sheets of highly fluid, compositionally uniform primitive olivine basalt erupt from rift zones and a central crater to build the volcano; Stearns (1946, p. 17) described the edifice as a shield-shaped dome. Eruptions are closely spaced in time; because of this and the high surface porosity that minimizes runoff, virtually no stream erosion occurs. Rare explosive eruptions may occur. All the volcanoes on Hawaii have already passed through this youthful stage.

Stage 3 of Stearns is characterized by collapse around the summit vent areas to form a caldera and subsidence along the rift zones to form craters and grabens. Eruptions continue to be frequent, and the lava continues to be of uniform composition. Explosive eruptions may occur slightly more frequently than during stage 2. Caldera walls prevent overflows of lava onto the flanks behind them, and so localized erosion and stream drainage may develop on sectors of the volcano not frequently covered by new lava. Kilauea and Mauna Loa are now in this stage.

Stage 4 is characterized by change in lava composition from primitive basalt to more alkalic types such as andesite and trachyte. These more viscous lavas fill any caldera, craters, and grabens and build a steeper sided cap. Explosive eruptions are common, ash is interbedded with lava, and cinder cones may be abundant. Intervals between eruptions are longer, and erosion increases; disconformities may separate successive flows and ash layers. Stearns (1946, p. 19) regarded Hualalai, Mauna Kea, and Kohala to be in this stage.

Stage 5 is dominated by stream and marine erosion. Local climate and exposure to prevailing winds and ocean currents determine the rate of erosion. The subsequent stages 6 (subsidence and reef building), 7 (emergence and renewed volcanism), and 8 (atoll and resubmergence) (fig. 7.5) have not yet been reached by the volcanoes of Hawaii; they are represented by volcanoes on other islands to the northwest.

This order of stages as proposed by Stearns (1946, 1966) culminated a century and a half of gradually improved understanding of the processes of growth and development of Hawaii and its sister islands. Subsequent studies have modified or redefined some of the stages, but much of the early foundation remains firm to the present day.

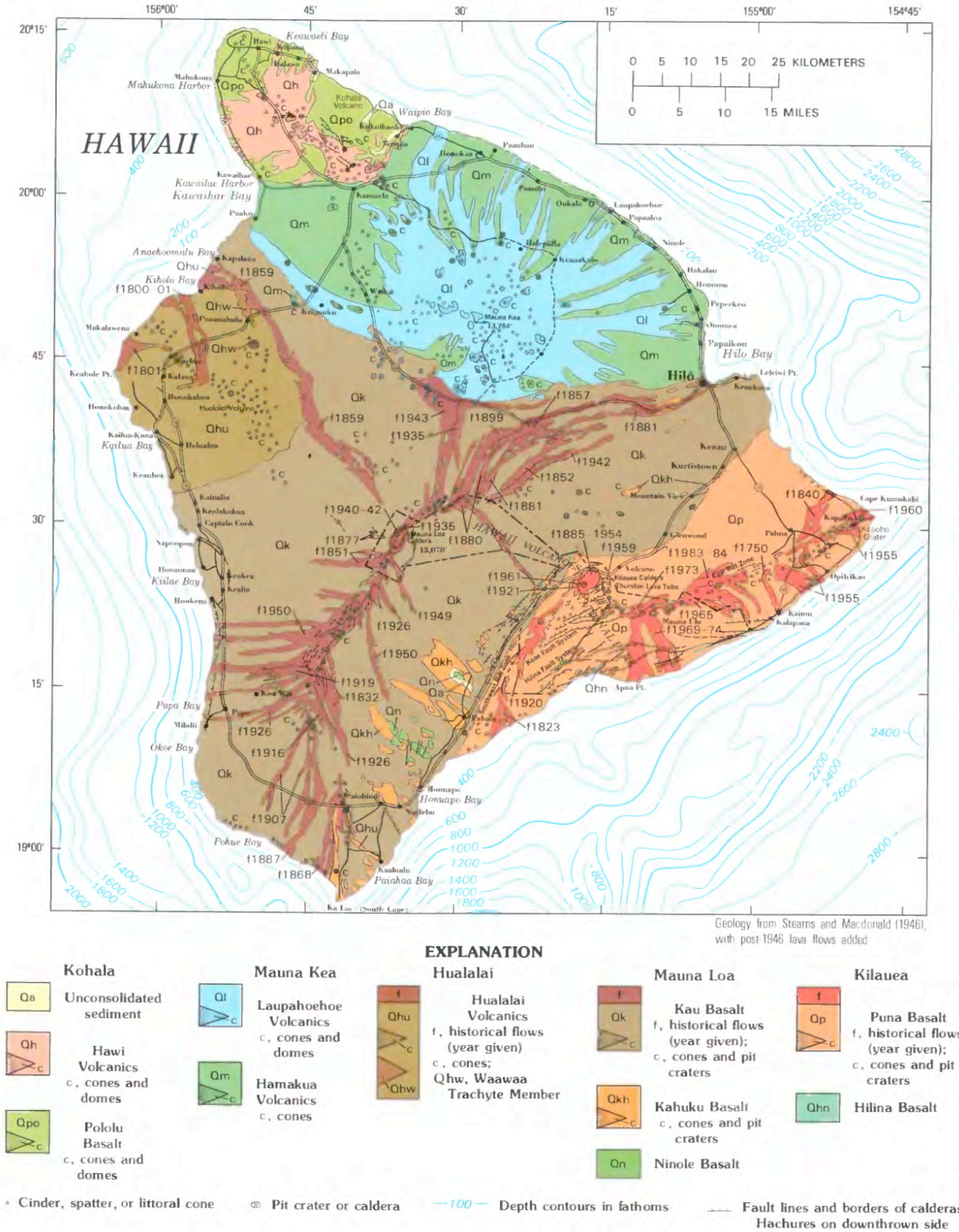

FIGURE 7.3.—Geologic map of Island of Hawaii. Geology from Stearns and Macdonald (1946), with lava flows from 1946 to 1984 added. Taken from American Association of Petroleum Geologists Geological Highway Map: Alaska and Hawaii (Circum-Pacific Edition, 1974); modified with permission from the American Association of Petroleum Geologists. Stratigraphic nomenclature from Langenheim and Clague (chapter 1, part II). Figure 7.4 shows correlation of geologic units among several volcanoes.

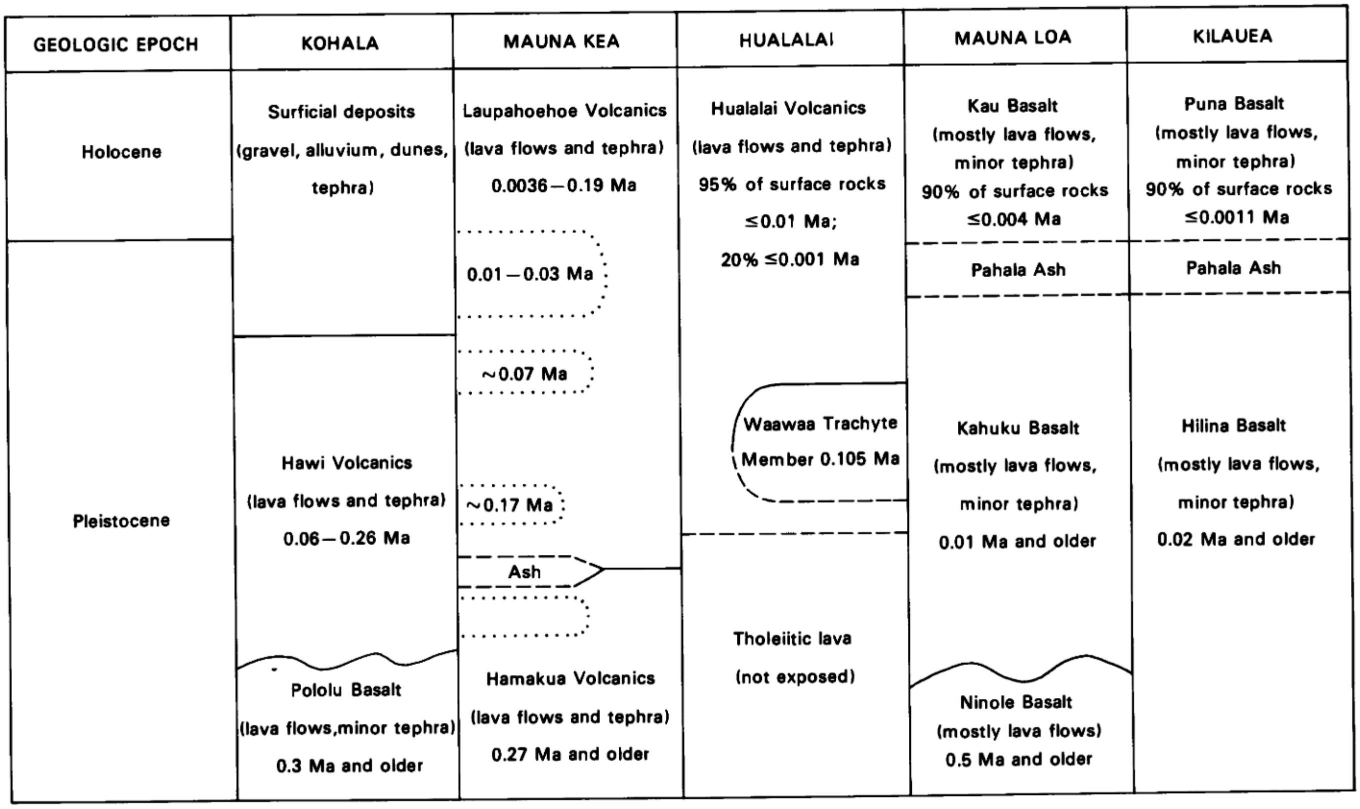

FIGURE 7.4.—Correlation chart showing major rock units on Island of Hawaii and their relative stratigraphic positions. Most names established initially by Stearns and Macdonald (1946), some units redefined by subsequent authors; relations shown here and nomenclature from Langenheim and Clague (chapter 1, part II). Numerical ages generalized from radiometric values given by various references cited in text. Dashed lines: indefinite, gradational, or controversial boundaries; dotted lines: glacial deposits (at Mauna Kea; from Porter, 1979a, 1979b); wavy lines: distinct hiatus.

DEVELOPMENTS SINCE THE MID-20TH CENTURY

The recognition and definition of the stages of island growth by Stearns (1946, 1966) were achieved in spite of severe limitations in the available evidence bearing on geologic history. The most significant limitations were these: (1) The submarine part of each volcano, which records the early geologic history, was inaccessible. (2) Present exposures reveal only the youngest rocks on most of the island's volcanoes. (3) Precise methods for dating basaltic lava had not been developed. We will consider the consequences of each of these limitations.

(1) Volcanoes are roughly conical in shape, so most of the volume of volcanic islands in the deep ocean lies below sea level. Bargar and Jackson (1974) used topography and bathymetry to measure the volumes of subaerial and submarine portions of the volcanoes of the Hawaiian-Emperor Chain; their results for the Island of Hawaii are shown in table 7.2. Only about 11 percent of the volume of the volcanoes of the island is above sea level, yet only the rocks and surface morphology of this part were available to Stearns and his associates for study. It is this small fraction that provided the evidence for Stearns' scheme of growth stages.

(2) Of this small subaerial fraction, erosion has penetrated the surface lavas only slightly or not at all on most volcanoes of the island. Even on Kohala and Mauna Kea, the most deeply eroded volcanoes, the exposed sections reveal but a small fraction of the geologic history. Hence the growth stages have been inferred chiefly from the most recent events as recorded by surface lavas and by analogy to the older, more deeply eroded volcanoes on the other islands. Even on older islands, however, erosion has only partly uncovered the subsurface rocks.

(3) Until the mid-20th century, fossils were the chief tool for determining rock ages, and few Hawaiian rocks contain fossils. Hence the only rocks that could be dated with much confidence were flows that had been emplaced during historical time. The dates of other geologic events were estimated by extrapolation of recurrence intervals of historical eruptions or inferred from rates of weathering, relative amounts of vegetation growing on old lava, degree and estimated rates of erosion, and stratigraphic relations among the exposed rocks. Even though such methods permitted conclusions to be reached, the lack of a way to measure numerical ages of basalt placed severe constraints on many geologic interpretations.

Since the time of the reports by Stearns (1946) and Stearns and Macdonald (1946), the gaps in knowledge have been narrowed through advances in a variety of disciplines, including geophysics, petrology, submarine geology, and radiometric and other dating techniques. Additional insights have been achieved through detailed

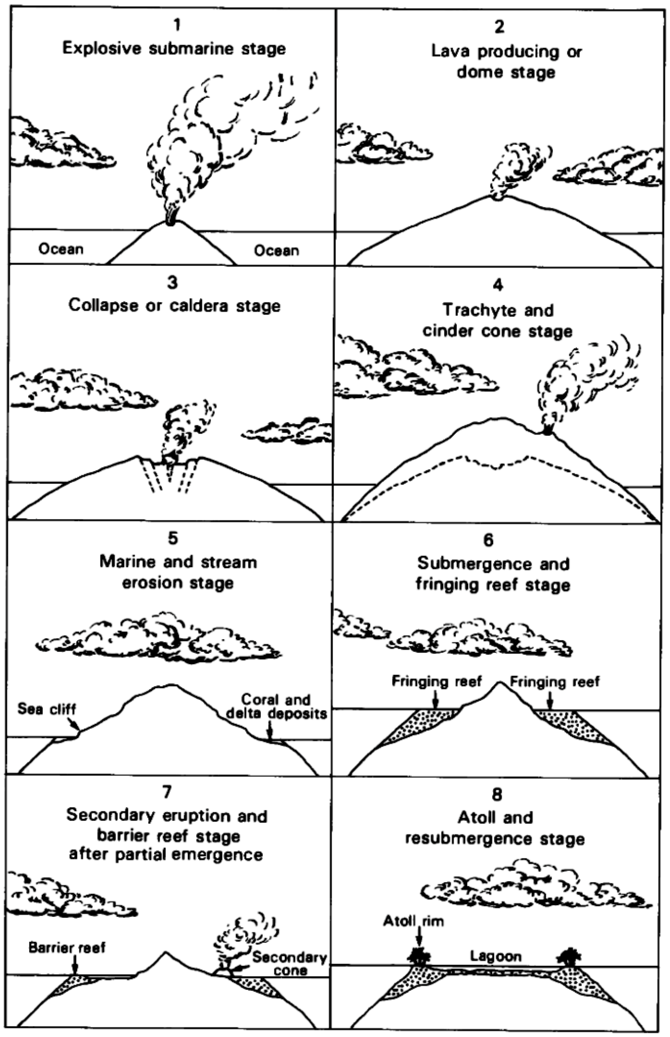

FIGURE 7.5.—Eight stages proposed by Stearns (1946) for geologic history of a volcanic island in the central Pacific.

geologic mapping of many areas, sophisticated applications of aerial photography, and sustained critical observations of a wide variety of eruptive activity. Findings at Loihi Seamount, 30 km offshore from the south coast of Hawaii, and its recognition as an active volcano have been of special value.

SUBMARINE INVESTIGATIONS

Investigations of submarine volcanism around Hawaii, including sea bottom photographs and studies of dredged samples, were begun in the 1960's. J.G. Moore and collaborators showed, for example, that at depths from 490 m to 5,190 m along the submarine extension of the east rift zone of Kilauea, virtually all the sea-floor material is fresh pillow lava, some of which is fragmental; nearby seamounts are composed of similar material, although most is less fresh and mantled with sediment (Moore and Reed, 1963; Moore, 1965). These studies found no indication of chemical exchange between erupting lava and sea water; rock composition, including water content, did not vary with depth. A progressive decrease in vesicle size, however, was observed to a depth of about 800 m, below which only microscopic vesicles were found. These findings confirmed the long-held inference that pillow lava is the dominant product of undersea basaltic eruptions of Hawaiian volcanoes. Pillow lava may also form when subaerially erupted lava enters the sea (Moore, 1975). The systematic relation between water depth and vesicle size apparently provided a tool by which the depth of eruption of submarine lava might be estimated. It was later found, however, that alkalic basalt dredged from Loihi at depths of 1–2 km has high vesicularity in comparison with tholeiitic samples collected at comparable depth (Moore and others, 1982, p. 91), demonstrating that vesicle size is a function of more than just depth of eruption.

The restricted development of vesicles in submarine tholeiites suggests that hydrostatic pressure of sea water inhibits vesiculation and explosive eruptions at depths below a few hundred meters (Moore, 1965). In contrast, explosive activity is common at the shoreline and in shallow depths, and it produces a zone of clastic debris intermixed with lava that extends from sea level to depths of several hundred meters (fig. 7.6). Explosive interactions occur between molten lava and sea water during shallow-water eruptions and also when subaerial lava flows enter the sea; the fragmented material may then be transported to cover deeper slopes. Fragmentation processes of explosion, implosion, thermal shock, and wave abrasion were observed at Kilauea from 1969 to 1973 during flows into the sea from Mauna Ulu (Moore and others, 1973; Peterson, 1976); the fragmented products are interleaved with coherent subaqueous lava flows, including pillow lava. Constructional submarine slopes are steep enough that slumping and landslides are common processes (Moore, chapter 2); near Oahu and Molokai, evidence has been found for truly huge submarine landslides (Moore, 1964). Slopes of the subaerial shields of the volcanoes are more gentle, in distinct contrast to steeper submarine slopes (Moore and Fiske, 1969). As the edifice grows through continuing eruptions, the clastic zone is covered by subaerially erupted lava, and it forms a layer between the submarine and subaerial lava that is a marker horizon extending through the volcano, preserving a record of the littoral and shallow-water processes and of subsidence of the island (fig. 7.6).

These and other investigations helped to characterize the submarine platform upon which the island rests and the behavior of lava in the presence of seawater. They are limited, however, to the exposed carapace and so do not give direct information about the internal core and the early history of the volcanoes. The recent recognition of Loihi Seamount as an active volcano, however, has furnished an opportunity to study an earlier stage in the growth of a Hawaiian shield volcano.

PETROLOGIC INVESTIGATIONS

Studies of Hawaiian lavas have made major contributions to igneous petrology during recent decades. The lavas are ideal for detailed investigations, because they reflect magma-generation and

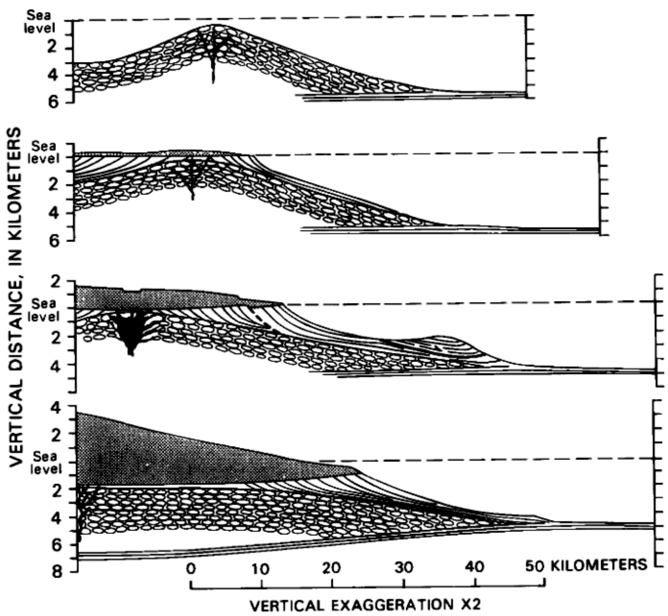

FIGURE 7.6.—Cross sections illustrating oceanic volcanic islands in submarine, sea-level, and subaerial stages of evolution (reproduced from Moore and Fiske, 1969, fig. 3, p. 1200). Patterns indicate rock types: ovals, pillow lavas with included pillow fragments and sediment; lined pattern, clastic rocks, including phreatic-explosion ash, littoral-cone ash, and flow-foot breccia and including some pillowed flows and pillow breccias; dark pattern, subaerial lava flows with minor ash; solid black, intrusive rock. Note contrast between submarine and subaerial slopes, continuation of clastic layer beneath subaerial shield, and downbowing of sea floor by subsidence caused by volcanic loading. Depth and elevation figures left side are in feet.

petrogenetic processes uncontaminated by assimilation of continental crustal rocks. Recent petrologic investigations of Hawaiian lavas are discussed in several papers elsewhere in this work (for example, Wright and Helz, chapter 23; Tilling and others, chapter 24), and the general petrologic development of the individual volcanoes of Hawaii is summarized later in this paper. Here we relate the growth stages established by Stearns (1946, 1966) to modern petrologic concepts and terminology.

The terminology applied to the lavas of Hawaii has shifted considerably during recent decades. In this paper we use the terms tholeiite and alkalic basalt and names for the other more differentiated lavas according to the usage adopted by Macdonald (1960) and Macdonald and Katsura (1961, 1962, 1964). They concurred with Powers (1935, 1955) that crystal fractionation alone cannot explain all of the chemical variation in rocks of the alkalic suite. Because no source materials for assimilation are available, Macdonald and Katsura (1961, 1962) suggested that volatile transfer and thermodiffusion might play a role in the differentiation processes. Another proposal was that wholly independent parent magmas produced the tholeiitic and alkalic suites (Kuno and others, 1957), but Macdonald and Katsura (1962) opposed this idea because of the small proportion of rocks representing alkalic magma. These and subsequent studies have retained the concept that voluminous and frequent eruptions of tholeiitic lava build a shield volcano (stage 2 of Stearns, 1946), with or without a summit caldera, and that this is followed by a transition to less frequent and less voluminous eruptions of more alkalic lava and tephra, which build a steeper sided carapace atop the shield (stage 4 of Stearns, 1946).

Petrologists have long sought to explain the origin of these two suites of lava. Samples of lava erupted at Kilauea Volcano from the 1950's to the present have helped relate eruptive behavior to the petrogenesis of tholeiitic magma (for example, Macdonald and Katsura, 1961; Murata and Richter, 1966; and Wright, 1973). Lava of the tholeiitic suite exhibits small but distinct chemical and mineralogical variations; most of these variations can be explained by the addition or subtraction of olivine, and hence such lava is referred to as olivine-controlled lava.

Powers (1955) first proposed the concept of distinct batches of magma derived from different parts of the mantle to explain variations other than those caused by olivine control. It was subsequently shown that olivine-controlled tholeiites of Mauna Loa appear to have been derived from a single batch of magma, whereas olivine-controlled tholeiites of Kilauea seem to have come from several separate batches (Wright, 1971; Wright and Fiske, 1971). Later work identified ten different chemical variants (magma batches) of Kilauea magma, which are mixed in varying proportions to produce the lavas erupted between 1968 and 1974 (Wright and others, 1975; Wright and Tilling, 1980). Trace-element contents of the tholeiites of Mauna Loa and Kilauea indicate derivation from more than one parent magma, confirming Powers' (1955) earlier deduction; the magma for each volcano was generated by distinctive partial-melting processes in different mantle source regions (Leeman and others, 1980). More recently, trace-element data suggest that olivine-controlled lavas of Mauna Loa, like those of Kilauea, also exhibit long-term compositional changes with time (Tilling and others, chapter 24; Budahn and Schmitt, 1985).

Wright (1984) proposed that Hawaiian tholeiite is the product of partial melting of mantle material that is residual from the material that earlier yielded midocean-ridge tholeiite and to which new components have been metasomatically added from a deeper melting source beneath Hawaii. This proposal is consistent with the distribution of trace elements and isotopes in the different tholeiites. These concepts provide a sound basis for the astute inferences by early workers that most of the volcano's volume, including much of the hidden portion of the shield, is constructed of tholeiite.

The subtle but significant compositional variations in Hawaiian tholeiites now provide problems and challenges that earlier workers, such as Cross (1915) and Washington (1923a, b, c) never anticipated, but the petrogenesis of the more alkalic lava poses a continuing challenge. Although much of the work on problems of alkalic magma has centered on other islands where more highly differentiated rocks are well represented, three of the volcanoes of the Island of Hawaii include alkalic rocks. Macdonald (1968) has provided a useful summary of the evidence that the alkalic and later suites of lava could be derived from the tholeiitic suite and that such derivation is compatible with the overall patterns of eruptive behavior. These and subsequently developed concepts on the origin of the alkalic suite are summarized by Clague (in press).

Samples dredged from Loihi provided some information with surprising implications for the composition of the deep interior of Hawaiian volcanoes. In addition to the anticipated tholeiite, the dredge hauls included transitional basalt, alkalic basalt, and basanite (Moore and others, 1982; Frey and Clague, 1983). Geochemical studies have led to the inference that the earliest erupted material was alkalic basalt; the initial melted material marking the onset of a new volcano may normally be of that composition (Frey and Clague, 1983). The wide compositional variety of dredge samples suggests that a transition from alkalic volcanism to the tholeiitic volcanism typical of the main growth stage of the shield may now be in progress. Palagonite coatings on the samples of alkalic basalt are thicker than coatings on tholeiite, suggesting that alkalic basalt is the older (Frey and Clague, 1983). Frequent seismic swarms (Klein and Koyanagi, 1979) suggest that Loihi is actively growing. Stratigraphic relations cannot be examined, and an alternate interpretation is that Loihi may now be at the end of the tholeiitic stage and only now is passing into the alkalic stage. The frequent seismicity however, as well as the relative thickness of palagonite, render this less likely. Still further implications of the geochemistry and petrogenesis of Loihi are discussed by Clague (in press). If Loihi is indeed passing from an initial alkalic stage to a tholeiitic stage, as proposed by Frey and Clague (1983), then alkalic volcanism is not solely confined to the waning stages of the life cycle of Hawaiian volcanoes. Even though it now serves as but a single example, findings at Loihi Seamount suggest that the hidden inner cores of Hawaiian volcanoes may record histories more complex than previously assumed.

AGE DETERMINATIONS

Until very recently, the lack of a method to date young basalts, the difficulty of correlating laterally discontinuous lava flows, and the scarcity of marker horizons placed severe limitations on stratigraphic studies in Hawaii. Even when radiometric dating techniques began to be developed and applied in the 1950's and 1960's, their usefulness on Hawaii appeared to be limited. The utility of the K-Ar method is constrained because Hawaiian rocks are very young and very low in potassium. As recently as the early 1970's, radiocarbon dating appeared to be applicable only to the few pyroclastic layers, because they contained the only obvious organic material intercalated among the lava flows. In spite of the difficulties, however, these and other radiometric techniques have subsequently been utilized to obtain numerical ages for many of the prehistoric lavas.

McDougall (1964) obtained K-Ar ages for rocks from several of the older Hawaiian Islands, but his initial effort to date samples from Hawaii (Kohala Volcano) was unsuccessful. However, refined sample preparation and improved techniques enabled a later study to succeed (McDougall and Swanson, 1972). The ages of Kohala rocks in the exposed part of the tholeiitic suite range from about 0.46 to 0.30 Ma, and ages of rocks in the alkalic suite range from about 0.26 to 0.06 Ma. These results established a position in the geologic time scale for the subaerial portion of Kohala Volcano, providing information on its growth rate, the interval between tholeiitic and alkalic volcanism, the duration of alkalic volcanism, and the date of last activity. Perhaps the only other exposed basaltic rocks on Hawaii old enough to be within the range of the K-Ar method are those of the Ninole Basalt on the south flank of Mauna Loa; these have yielded K-Ar ages from more than 0.5 to less than 0.1 Ma (Evernden and others, 1964, p. 156–158). A chronology for both volcanism and glaciation on Mauna Kea was established with the aid of K-Ar and radiocarbon techniques (fig. 7.4; Porter, chapter 21, 1979a, 1979b; Porter and others, 1977).

Initial attempts at radiocarbon dating of Hawaiian samples in the 1960's were confined to carbonized residues found in ash layers; results were not then published. During the early systematic geologic mapping of Mauna Loa in the mid-1970's, methods for finding carbonized organic remains beneath lava flows were improved, providing considerable material for radiocarbon dating (Lockwood and Lipman, 1980). This led to many successful radiocarbon age determinations for lava flows on the volcanoes of Hawaii (Rubin and others, chapter 10; Kelley, 1979; Kelley and others, 1979). However, application of the radiocarbon method is constrained both by its upper limit of 30–40 ka, depending on sample characteristics, and by the restricted distribution of datable carbon associated with lava flows. Woody residues are confined to zones near the margins of lava flows that have invaded vegetated areas, so the method cannot be used for flows above the tree line or in other barren areas nor for portions of lava flows that do not lie near a margin.

Many lavas of Hawaii are too old for radiocarbon dating and too young for K-Ar age determination. A technique that may provide ages within this gap is thermoluminescence (TL). This technique relies on an incompletely understood phenomenon in which light is emitted by certain minerals as they are heated toward the point of incandescence (Berry, 1973; May, 1979). Berry (1973) conducted experiments testing the feasibility of TL as a dating technique for Hawaiian rocks and concluded that the method holds promise. Subsequently more elaborate experiments yielded reasonably consistent results for feldspar from rocks of the alkalic suite for ages from about 250 to 2.5 ka (May, 1979, p. 40). Results for feldspar-poor tholeiitic rocks were not as consistent, but May (1979, p. 41) expressed the belief that a dating technique using TL could ultimately be developed for tholeiites through a range from about 100 to 10 ka.

Another method of dating uses the secular variation of the earth's magnetic field. As iron-titanium oxides in newly erupted lava cool through the Curie temperature, they assume and preserve the direction of magnetism of the earth's field at that time and place. Geomagnetic studies take advantage of this characteristic to construct a history of the changes in orientation of the magnetic field, using rocks that can be dated independently. By matching the magnetic direction of a rock of unknown age to the local geomagnetic history, the possible age(s) of the unknown rock can be determined. Working with lavas already dated by the radiocarbon method, Holcomb (1980) derived the history of the secular variation of the magnetic field in Hawaii for the past 2,500 yr and in turn has applied it to obtain ages for most of the surface flows of Kilauea Volcano. Although this method ultimately depends on radiocarbon ages, samples for study are not restricted to the vegetated zones where datable carbon may occur. The dates obtained through this approach enabled Holcomb (chapter 12, 1980) to determine that 90 percent of the surface rocks of Kilauea are younger than 1.1 ka.

The increasing degree of weathering with increasing age has long been used to estimate visually the relative ages of lava flows. To see if weathering could be used to derive numerical ages, Halbig and others (1979) correlated the thickness of alteration rinds on basaltic glass with radiocarbon ages of the same lavas. They found that the rind thickens at an average rate of about 1.05 mm/100 yr during the first 1,000 years; thereafter rates become unreliable because of mechanical attrition and spalling. They recognized the potential effects of variations in climate and glass composition but did not study those effects. This technique, even with its probable limitations, has the advantages of being quicker, simpler, and less expensive than radiometric and paleomagnetic age determination, and it may prove useful for qualitative and semiquantitative estimates of age.

CALDERAS AS RELATED TO VOLCANO DEVELOPMENT

Dutton (1884, p. 142–143) suggested that caldera formation was a recurring process during the growth of Hawaiian volcanoes, but the proposal by Stearns (1940, 1946) that a single caldera forms at the end of shield growth was tacitly accepted by most workers until recently (Holcomb, chapter 12, 1976, 1980). Macdonald (1965) reviewed possible mechanisms for the formation of Hawaiian calderas and concluded that most commonly piecemeal collapse occurs above a shallow magma reservoir when magma is withdrawn by either voluminous eruption or intrusion along a rift zone. Macdonald further reasoned, in accord with the ideas of Stearns, that a volcano must achieve a state of maturity for a magma reservoir to have grown to a sufficiently large size for magma withdrawal to be able to trigger collapse. Calderas exposed by erosion at older volcanoes, such as Kohala on Hawaii as well as some on other islands, formed originally within tholeiitic lavas but were later filled by transitional or alkalic lavas. Although such evidence is permissive only, it supports the idea that calderas form at the conclusion of tholeiitic shield building (Stearns, 1940, 1946, 1966; Macdonald, 1965).

Macdonald (1965) considered many hypotheses before selecting a preferred mechanism for caldera formation, but he did not explicitly consider the possibility that such formation might occur more than once. Powers (1948) had suggested the existence of an earlier caldera at Kilauea on the basis of discrepant elevations of young ash beds and partially obscured surface structures. Using additional evidence, Holcomb (chapter 12, 1976, 1980, p. 194) concluded that the present caldera of Kilauea is nested within a prehistoric caldera that had been filled and nearly buried. He also noted evidence for an earlier caldera at the summit of Mauna Loa (Holcomb, 1976). If his conclusions are correct, the presence of a caldera is neither a sufficient nor necessary condition to infer a specific stage in the life cycle of a volcano, and the possibility exists, within any Hawaiian volcano, that a succession of calderas may lie buried.

This viewpoint is supported by results from Loihi, where a bathymetric survey revealed a summit depression approximately 70 m deep, and measuring about 2.8 km by 3.7 km, which includes two pit craters of about 0.8 and 1.2 km in diameter, each of which is more than 250 m deep (Malahoff, chapter 6; Malahoff and others, 1982; summarized by Macdonald and others, 1983, p. 117–118). If Loihi is accepted as a volcano in an early stage of its evolution (see section "Petrologic Investigations"), it provides an additional example of caldera formation at a stage other than near the end of the main growth of a Hawaiian volcano.

This change in thinking is reflected by Macdonald and others (1983, p. 146–149), who no longer specify the development of a caldera as an individual stage in the development of a volcano, but rather include it simply as an event that may happen during the shield-building stage. We concur with this usage and further advocate avoiding the characterization of the transition from tholeiitic to alkalic magmatism by the use of terms such as "caldera-filling" and "post-caldera." These shifts in viewpoints are incorporated in our proposed modifications to the scheme of growth stages for Hawaiian volcanoes, outlined in a subsequent section.

STRUCTURAL DEVELOPMENT OF HAWAIIAN VOLCANOES

The shield volcanoes of Hawaii have broad bases in relation to their height and subaerial slopes in the tholeiitic stage, unmodified by faulting or erosion, generally of 3°–10° and averaging about 6°. Volcanoes with a steeper sided alkalic cap have summit slopes that locally approach 20° and average about 12°. The subaerial part of each volcano is built of tens or hundreds of thousands of discrete, overlapping lava flows of pahoehoe and aa that radiate outward from a central summit vent area and from two or more linear rift zones. Beds of tephra may be interlayered sporadically with the tholeiitic lava, and the proportion of tephra to lava increases during the growth of the alkalic cap.

Some descriptions state that lava flows have the form of sheets (see Stearns, 1946, p. 17; Stearns and Macdonald, 1946, p. 24), an impression easy to derive because their thickness is small compared to their lateral dimensions. However, the geologic map (fig. 7.3; Stearns and Macdonald, 1946, plate 1) shows that for most flows the ratio of length to width is large, and it seems preferable to visualize flows as elongated tongues or lobes (Peterson, 1971, p. 163–164). This visualization helps emphasize the across-flow discontinuity of Hawaiian flows, which is one of the major problems in efforts to establish consistent stratigraphic correlations. Adjacent volcanoes generally grow contemporaneously, and their flows are commonly interdigitated.

Slopes on the submarine part of the volcano are steeper than on the subaerial part; they are commonly 10°–20° (fig. 7.6). Submarine flows are dominantly of pillow lava and are assumed also to be tongue-shaped, like subaerial flows. Superimposed upon and incorporated within this primary edifice of overlapping lava flows and sporadic tephra layers are a number of structures that develop throughout the growth of the shield, including rift zones, faults, landslides, calderas, craters, and tephra and spatter cones.

Rift zones have long been recognized as integral structural elements of Hawaiian volcanoes (Dana, 1849; Dutton, 1884). The summit areas and rift zones include almost all vents through which lava is erupted, and the surfaces of the rift zones of Kilauea and Mauna Loa are marked by spatter cones, spatter ramparts, pit craters, grabens, faults, cracks, and fissures, which constitute a record of repeated active volcanism and related ground dislocations. Where the subsurface portions of rift zones have been exposed by erosion on the older islands, they are marked by abundant closely spaced subparallel dikes, which demonstrate that rift zones tend to maintain consistent orientation and position throughout the growth of a shield.

Fiske and Jackson (1972) proposed that the orientations of rift zones on volcanoes that grew from the ocean floor, distant from other volcanoes, is determined by regional stress patterns; at volcanoes that grew on the flank of an already existing edifice, the orientation of the rift zones is determined by the gravitational stress field influenced by the buttressing effect of the older volcano. Their hypothesis is supported by results of experiments with gelatin models and is basically consistent with the progression of development of the volcanoes on all the islands from Kauai to Hawaii (see, for example, Moore, chapter 2, fig. 2.6). Their analysis yields the following sequence of origin for the volcanoes of Hawaii: Kohala, Hualalai, Mauna Kea, Mauna Loa, and Kilauea (fig. 7. 7). This sequence of origin is not necessarily the same as either the order of petrogenetic development or the time progression of known eruptions; for example, hawaiite on Mauna Kea is more differentiated than alkalic basalt on Hualalai, and historical activity has occurred at Hualalai but not at Mauna Kea. These relations suggest that Mauna Kea has passed through the petrogenetic development sequence more rapidly than Hualalai.

The model of Fiske and Jackson (1972) provides a generally consistent explanation for the orientations of rift zones and for many aspects of the behavior of the different volcanoes. As adjacent volcanoes commonly grow contemporaneously, however, fluctuations of eruption rates and shifts of vent sites from summit to rift zone in one volcano may cause changes in slope direction or in the influence of buttressing, thereby affecting the prevailing stress fields of an adjacent volcano and influencing the development of its rift zones. Stearns and Clark (1930) noted, for example, that the growth of Kilauea against the southeast flank of Mauna Loa caused a change in the pattern of behavior of the nearby fault systems of Mauna Loa. Lipman (1980) concluded that the growth of Kilauea has, in effect, squeezed the northeast rift zone of Mauna Loa and effectively sealed off its lower, easternmost extension and that it has caused the

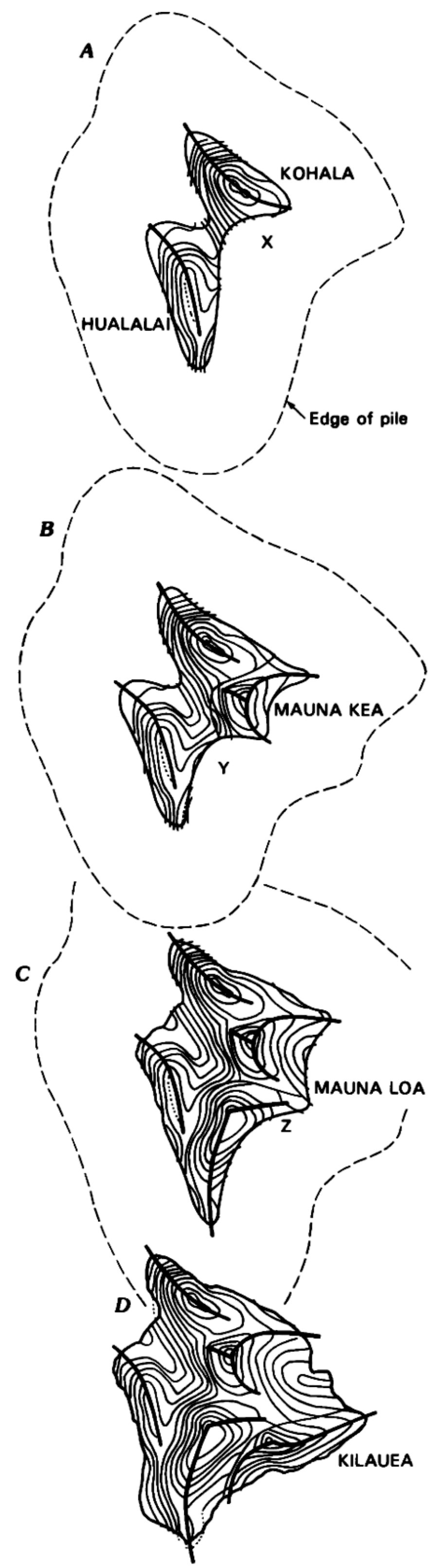

FIGURE 7.7.—Growth of Island of Hawaii as proposed by Fiske and Jackson (1972, fig. 11, p. 315). Reproduced by permission. *A*, Early formed Kohala-Hualalai edifice; X marks site of future Mauna Kea. *B*, Later stage; Y marks site of future Mauna Loa. *C*, Still later stage; Z marks site of future Kilauea. *D*, Present configuration. Each sketch shows orientations of rift zones, which developed in accord with prevailing regional or gravitational stress patterns.

southwest rift zone of Mauna Loa to migrate gradually westward. Such changes support the basic concept of Fiske and Jackson (1972) that rift zones develop in accord with the prevailing stress field, although they require modification of the idea that the rift zones remain fixed in position and orientation.

Pertinent to these issues is the orientation of the rift zones of Loihi Volcano. The bathymetric contours along the south flank of the island are oriented about N. 60° E. (fig. 7.8*A*); according to the concept of Fiske and Jackson (1972), the rift zones of Loihi should lie approximately parallel to this direction. Instead, the orientation of the elongate ridges inferred to mark the rift zones is mostly about N. 30° W., varying locally to due north and N. 10° E. (fig. 7.8*B*); it thus is chiefly almost at right angles to the expected orientation (Malahoff, chapter 6; Malahoff and others, 1982; Moore and others, 1982). Too little is known about the details of the structure and morphology of Loihi to fully evaluate this apparent discrepancy, but it may be noted that the rift zones of Loihi are approximately parallel to the line of the major loci of volcanoes to the northwest (fig. 7.8*A*; Malahoff, chapter 6). The central vent of Loihi lies approximately along the projection of the 4,000-m depth contour, approximately 1,000 m above the level of the regional ocean floor (fig. 7.8*A*). It may be that during the early growth of Loihi, the influence of the regional stress pattern predominated over that of the gravitational stress field on the flanks of the older volcanoes, or perhaps Loihi began before the submarine slopes of Kilauea and Mauna Loa had advanced to the Loihi site. As Loihi grows, it will offer a variety of tests for the Fiske-Jackson (1972) hypothesis and will be a fascinating subject for study by future generations of scientists.

The gravitational stress field on volcano flanks influences the structure in still another important way. Landslides have long been recognized as a hazard in Hawaii, occurring chiefly on steep slopes such as seacliffs and stream-cut valley walls; they are commonly induced by saturation of the ground by heavy rains, by shaking from earthquakes, or especially by the two in combination. In contrast to these relatively small, frequent landslides, Moore (1964) advocated large-scale landsliding as the origin for extensive areas of irregular submarine topography offshore from several islands, including Hawaii. Masses covering several thousand square kilometers north of Molokai and north of Oahu are inferred to be two immense landslides that moved more than 100 km along slide planes with an average slope of about 2°. As more detailed bathymetry has become available for offshore areas around Hawaii, it has been recognized that landslides are common on the submarine flanks of volcanoes. Some large-scale slumping events may be related to step-faulting on the subaerial seaward flanks of volcanoes, such as in the Hilina fault system on the south flank of Kilauea (Moore and Fiske, 1969, p. 1199–1200). Certain bathymetric details of Loihi are also inferred to be the result of submarine landslides (Malahoff, chapter 6).

Moore and Krivoy (1964) proposed that gravity-induced seaward movement of the south flank of Kilauea caused dilation of its east rift zone, leading to permissive emplacement of dikes by magma from the summit reservoir. This idea was tested when detailed analyses of the displacements of points on the east rift zone, the

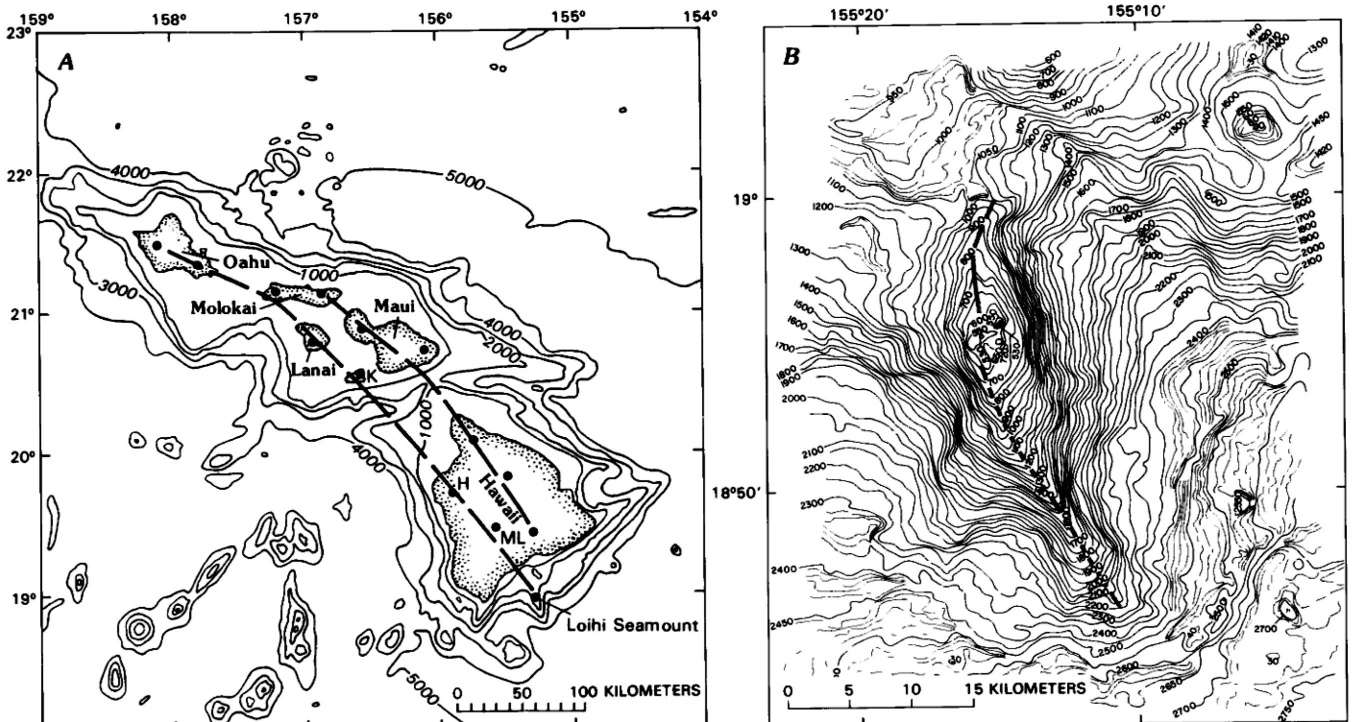

FIGURE 7.8.—Loihi Seamount. ***A***, Position along regional curved locus extending through western line of volcanoes from Oahu to Hawaii, including Hualalai and Mauna Loa Volcanoes (after Moore and others, 1982). Bathymetric contours in meters. ***B***, Bathymetric map (after Malahoff and others, 1982). Elongate ridges extending south-southeast and north from summit are major rift zones of volcano. They lie subparallel to volcano locus shown in *A* instead of parallel to submarine contours of island platform. Depth contours in fathoms (1 fathom = 1.83 m).

Koae and Hilina fault systems, and other parts of the south flank were made by Duffield (1975) and Swanson and others (1976a). They examined the amount, direction, and time of displacement as related to the time and place of eruptions and concluded that displacements on the rift zone and south flank were caused by forcible injection of magma into the rift zone, rather than the rift zone being dilated as a result of faulting and sliding of the south flank and permissively allowing magma to enter. Nevertheless, gravity plays an important role, because displacements are toward the sea in the unbuttressed direction. Hence these findings are compatible with those of Fiske and Jackson (1972) concerning the role of gravity in the development of the east rift zone.

The $M=7.2$ earthquake at Kilauea on November 29, 1975, was probably related to strains accumulated throughout the south flank from intrusion of dikes into the rift zone (Swanson and others, 1976a; Tilling and others, 1976). However, the earthquake itself has been determined to be the result of abrupt southward movement of the south flank edifice across the underlying oceanic crust (Ando, 1979; Furumoto and Kovach, 1979; Crosson and Endo, 1981, 1982). This movement induced extensive displacements throughout the Hilina and other fault systems (Tilling and others, 1976).

Marine terraces positioned both above and below sea level (Stearns and Macdonald, 1946) have long suggested that the level of the sea fluctuated over extended periods of time; they have been interpreted both as eustatic and as related to local crustal movements. Submergence of cultural artifacts of the early Hawaiian people indicates that Hawaii is currently subsiding (Apple and Macdonald, 1966). This inference was supported by a study of tide-gage records, which yielded a rate of subsidence at the Hilo tide gage of about 4.1 mm/yr, implying an annual volume rate of subsidence of the east end of the Hawaiian Ridge of about 0.27 km^3/yr (Moore, 1970). The rate of subsidence at Hilo has subsequently been redetermined to be 2.4 mm/yr, giving a recalculated volume rate of subsidence of 0.075–0.1 km^3/yr (Moore, chapter 2). The sinking of Hawaii is interpreted to be the result of crustal loading by the erupted products. The new volume rate of subsidence agrees closely with the figure of 0.11 km^3/yr, which recently has been the average annual volume of lava erupted by Kilauea (Swanson, 1972).

Marine deposits now above sea level are difficult to explain if progressive subsidence is the result of eruption and crustal loading. However, recent reinterpretation of such deposits as resulting from a giant ocean wave permits the interpretation that Hawaii, instead of alternately rising and sinking, has indeed been sinking persistently in response to long-sustained crustal loading (Moore and Moore, 1984).

Moore (chapter 2) demonstrates that the constructional volcanic edifices, instead of merely resting on the deep ocean floor at a depth of 5–6 km as previously believed, have bowed the crust downward during and after their growth, that most of their bases have subsided about 8–10 km, and that since reaching the sea surface the volcanoes have subsided 2–5 km. Hence a substantial part of their mass that is now below sea level was erupted subaerially.

HISTORICAL ACTIVITY

Among Hawaii's volcanoes, only Kilauea and Mauna Loa have erupted since the time of the missionaries, but they have in that interval been among the world's most active volcanoes. A summary of their activity is provided in tables 7.3 and 7.4.

When first known to the outside world, Kilauea became famous for its long-lasting lava lake in the crater and vent complex of Halemaumau inside the summit caldera. Lava in the lake circulated, fountained, and alternately rose and fell within Halemaumau Crater. The lake episodically overflowed onto the caldera floor and, during its 101-year life span, added about 2 km^3 of lava to the caldera, raising the floor several hundred meters. This lava constructed a gently sloping shield volcano inside the caldera, with the summit at Halemaumau. A few eruptions also occurred during this time along the east and southwest rift zones of Kilauea, but most activity was concentrated in the summit caldera. The lava-lake activity ended in 1924 with subsidence and explosive eruptions at Halemaumau, which left the pit crater more than 400 m deep.

During the next few years, brief episodic eruptions occurred at Halemaumau and partly filled the pit crater formed in 1924, but a period of repose followed from the mid-1930's to 1952. Since then, Kilauea has had more than two dozen eruptions within the caldera and nearby summit area as well as along both rift zones, extruded more than 1.3 km^3 of lava, and exhibited a very wide variety of behavior (see references in table 7.3). Most eruptions since the 1960's have occurred along the east rift zone. Individual eruptions have lasted from less than a day to more than two years. Episodic activity at Puu Oo, in the central east rift zone, began in January 1983 and continues as of early 1986 (Wolfe and others, chapter 17).

Mauna Loa erupted 35 times between 1832 and 1950 (table 7.4), an average of one eruption every 3.4 years. Eruptions showed a tendency to alternate between the summit area and either the northeast or southwest rift zone. Intervals between eruptions ranged from as brief as 4 months to as long as 11 years, and eruptions lasted from less than a day to 547 days. The native Hawaiians had no traditions or stories about Mauna Loa eruptions, so the length of the period of quiescence preceding 1832 is not known. Because the summit and upper rift zones are remote from Hawaiian villages, small eruptions may have gone unobserved; alternatively, a prolonged period of actual quiet may have prevailed. The latter seems much more likely, as eruptions of the type occurring in the nineteenth and twentieth centuries would have been obvious to the Hawaiians and would have influenced their activities. Following the eruption of 1950, the volcano did not erupt again until 1975, when a one-day-long eruption ended the longest period of quiet in historical time (Lockwood and others, chapter 19, 1976). The most recent activity occurred in 1984, when a 22-day-long eruption sent lava flows to within 18 km of the waterfront at Hilo and 6 km of the outskirts of the city (Lockwood and others, chapter 19, 1985)

The frequent activity of both these volcanoes suggests that similar patterns of behavior are likely to continue during the near future. Holcomb (chapter 12, 1980), however, has analyzed the long-range shifts in type and location of activity of Kilauea and has developed a model indicating major shifts from summit growth and caldera filling to rift-zone growth and summit collapse. Equivalent patterns of shifting behavior at Mauna Loa are being reconstructed by Lockwood and Lipman (chapter 18).

REVISED SCHEME OF EVOLUTIONARY STAGES FOR HAWAIIAN VOLCANOES

The evolutionary stages defined by Stearns (1946) have served as a basic framework for Hawaiian geologic history for about four decades. Macdonald and Abbott (1970, p. 138) modified the stage boundaries to reflect improved knowledge of submarine processes and subdivided the first stage of Stearns into deep and shallow submarine stages. Later, Macdonald and others (1983, p. 147–149) recognized that calderas are not necessarily unique to a specific stage in the growth of the volcano, and their updated classification omitted the caldera stage.

Other investigators have emphasized four stages that are of significance in the petrologic evolution of Hawaiian volcanoes, roughly patterned after the initial definitions by Stearns (1940). Although the various workers have been consistent in designating four stages, they have selected different ways of defining their progression. Stearns (1940) initially defined them as (1) youthful, shield-building (chiefly olivine-bearing basalt); (2) mature, caldera formation (also olivine-bearing basalt); (3) old age, caldera filling (differentiated rocks); and (4) rejuvenated or post erosion (highly differentiated rocks); Stearns later (1946, 1966) added non-eruptive developmental stages. Tilley (1950) reiterated the same four stages of Hawaiian volcanism. Leeman and others (1980) redefined them as (1) shield-building stage (tholeiitic lava); (2) caldera-filling stage (tholeiitic, transitional, and mildly alkalic lava); (3) postcaldera stage (including alkali olivine basalt and related differentiates); and (4) posterosional stage (including basanitic and nephelinitic lavas). The chief difference in their scheme is that the formation of calderas has been included with shield building, and a caldera-filling stage has been substituted for the second stage and serves as the transition from tholeiitic to alkalic basalt. A different variant is offered by Clague and Dalrymple (chapter 1, part I, table 1.1). Their four stages are (1) preshield stage (including basanite, alkalic and transitional basalt); (2) shield stage (tholeiitic basalt and picritic tholeiitic basalt); (3) postshield alkalic stage (alkalic lavas of assorted composition); and (4) rejuvenated stage (alkalic lava and highly differentiated types such as basanite and nephelinite). Their stage (1) reflects the new findings at Loihi, and their stage (3) is equivalent to the latter part of stage (2) and all of stage (3) of Leeman and others (1980). The scheme of evolution to be offered here utilizes the four stages as defined by Clague and Dalrymple (chapter 1, part I), although the terms used for some of the stages are different, and additional stages are defined.

Earlier discussion (see section "Calderas as Related to Volcano Development") established our view that it is not appropriate to retain a separate stage of caldera formation. By the same arguments it is also inappropriate to designate another stage as postcaldera. For example, if either Kilauea or Loihi caldera is filled by new lava in the future, as seems quite likely, the subsequent activity in reality would be postcaldera, but the composition will most likely still be tholeiitic. This lava would certainly not meet the essential evolutionary criteria required of the so-called postcaldera stage, which some of the above authors have specified as reflecting the differentiation to alkalic magma. It is also possible for the magma of a volcano to undergo differentiation to the alkalic suite without the volcano having had a caldera (for example, no evidence has yet been found for a caldera at Hualalai, though it is possible that unknown filled calderas lie within the edifice). In view of these several considerations, we feel the name "postcaldera stage" is a misnomer and its use should be avoided.

Our intention is to propose a scheme of evolution with the same purpose as that by Stearns (1946) and subsequently modified by Macdonald and Abbott (1970) and Macdonald and others (1983)—to outline in simple form the major steps in development of a typical Hawaiian volcano. Such schemes are of necessity oversimplified because of the variations and exceptions followed by individual volcanoes, yet they are useful as a framework or standard of comparison, and most importantly they can serve as a spur in the search for improved understanding. The stages here include not only the growth of the volcano as reflected by petrogenetic developments reviewed just above, but they also include other significant geologic processes and environmental conditions. Some of the terms used by preceding authors have been retained, but others have been revised, either because of redefinition of a stage reflecting a modified current concept or simply because another term seemed more appropriate. The terms adopted avoid rock names because we find it difficult to apply a petrologic term without introducing some ambiguity. Furthermore, all reference to a caldera in the terms and in the definitions of stages has been removed because we hold the opinion that calderas may repeatedly form and be refilled at various times during the rapid growth of a shield; thus their development and filling is not sufficient to define a distinct stage. The terms here also avoid the prefixes pre- and post-, as associated with a process or a feature, because their use implies, sometimes erroneously, that this process or feature does not operate.or exist at all during the designated stage. We wish to emphasize that the successive stages may overlap and intergrade, and the processes characteristic of two or more stages may be operating at different places on a volcano at the same time. Furthermore, volcanoes do not necessarily pass through every stage, nor do different volcanoes necessarily progress through stages at similar or consistent rates.

In spite of the advances since 1946, such as new geophysical and geochemical tools, improved investigative techniques, and extensive offshore submarine exploration, our concepts of volcano development are still based on facts derived from only a thin outer shell of the Hawaiian volcanoes. Petrological theories have made exciting and possibly valid inferences about the petrogenesis of magma and the growth of the volcanoes, but until these ideas can be tested by actually probing the deep interior and the base of several volcanoes, the concepts must remain speculative. So although the scheme proposed here represents an effort to reflect currently prevailing ideas as unabiguously as possible, it still suffers from some

TABLE 7.3.—*Historical eruptions of Kilauea through May 1985*

[Dashes (---), no data; query (?), questionable data]

Date eruption began: Year	Month and day	Duration (days)	Location of major vent(s)	Approximate area (km²)	Approximate volume ($m^3 \times 10^6$)	References
1750(?)	---	---	East rift	4.1	14.9	Holcomb, chapter 12, 1980.
1790(?)	---	---	-- do	7.9	28.8	Holcomb, chapter 12, 1980.
1790	November (?)	---	Caldera (explosive)	(Blocks lapilli, ash)	---	Brigham, 1909, p. 36–39; Hitchcock, 1909, p. 165–167; Swanson and Christiansen, 1973; Decker and Christiansen, 1984.
1823	---	---	Southwest rift	10.0	11.5	Hitchcock, 1909, p. 163; Stearns, 1926.
1823	---	101 yr (intermittent)	Caldera, Halemaumau	8.2	2,000.0	Ellis, 1827, p. 163–176; Brigham, 1909, p. 40–222; Hitchcock, 1909, p. 179–182, 186–188, 191–194, 198–206, 210–260; Jaggar, 1947, p. 9–169, 216–314.
1832	January 14	---	East rim of caldera	---	---	Brigham, 1909, p. 46; Hitchcock, 1909, p. 182–185.
1840	May 30	26	East rift	17.1	215.0	Coan, 1841; Brigham, 1909, p. 50–55; Hitchcock, 1909, p. 188–190.
1868	April 2	---	Kilauea Iki	.2	---	Brigham, 1909, p. 106–110; Hitchcock, 1909, p. 207.
1868	April 2	---	Southwest rift	.1	.2	Brigham, 1909, p. 109–119; Hitchcock, 1909, p. 207–210; Coan, 1869.
1877	May 4	1	Caldera wall	---	---	Brigham, 1909, p. 131–132; Hitchcock, 1909, p. 217.
1877	May 21 (?)	---	Keanakakoi	.1	---	Brigham, 1909, p. 132; Hitchock, 1909, p. 217.
1884	January 22	1	East rift (submarine)	---	---	Stearns and Macdonald, 1946, p. 111; Macdonald and Abbott, 1970, p. 75.
1879	July 14	1 (?)	Distinct episodes of Halemaumau overflows and (or) caldera fissure outbreaks. These are part of the 1823 101-year-long summit eruption. Earlier lava buried; lava from those episodes locally exposed in caldera.	---	---	Brigham, 1909, p. 133, 140; Hitchcock, 1909, p. 219.
1882	September	3 yr		---	---	Brigham, 1909, p. 156–158; Hitchcock, 1909, p. 221–226.
1888	July	310		---	---	Dana, 1890, p. 123.
1892	April	730 (intermittent)		---	---	Brigham, 1909, p. 184–191.
1918	February 23	14		.1	.2	Jaggar, 1947, p. 112.
1919	February 7	294		4.1	26.0	Jaggar, 1947, p. 118–125.
1921	January	60 (approx)		2.0	6.7	Jaggar, 1947, p. 149–151.
1919	December 15	221	Southwest rift (Mauna Iki)	13.0	47.0	Jaggar, 1947, p. 137–146.
1922	May 28	2	East rift (Makaopuhi, Napau)	.1	---	Jaggar, 1947, p. 155–157.
1923	August 25	7	East rift	.5	.1	Jaggar, 1947, p. 161.
1924	May 10	17	Caldera (explosive)	(Blocks)	---	Jaggar and Finch, 1924; Jaggar, 1947, p. 162–168, 205–259; Decker and Christiansen, 1984.
1924	July 19	11	Halemaumau	.05	.24	Jaggar, 1947, p. 168–169.
1927	July 7	13	-- do	.1	2.42	Jaggar, 1947, p. 175–176.
1929	February 20	2	-- do	.15	1.47	Jaggar, 1947, p. 180–181.
1929	July 25	4	-- do	.2	2.75	Jaggar, 1947, p. 181–182.
1930	November 19	19	-- do	.23	6.48	Jaggar, 1947, p. 185–186.
1931	December 23	14	-- do	.3	7.37	Jaggar, 1947, p. 186–189.
1934	September 6	33	-- do	.4	7.26	Jaggar, 1947, p. 197.
1952	June 27	136	-- do	.6	49.0	Macdonald, 1955, 1959.
1954	May 31	3	Halemaumau, caldera	1.1	6.5	Macdonald, 1959; Macdonald and Eaton, 1957.
1955	February 28	88	East rift	15.8	92.0	Macdonald, 1959; Macdonald and Eaton, 1964.
1959	November 14	36	Kilauea Iki	.6	51.0	Richter and Eaton, 1960; Macdonald, 1962; Richter and others, 1970.
1960	January 13	36	East rift	10.6	120.0	Do.
1961	February 24	1	Halemaumau	.05	.02	Richter and others, 1964.
1961	March 3	22	-- do	.8	.27	Do.
1961	July 10	7	-- do	1.0	13.2	Do.
1961	September 22	3	East rift	.8	2.3	Do.
1962	December 7	2	-- do	.05	.33	Moore and Krivoy, 1964.
1963	August 21	2	East rift (Alae)	.2	.04	Peck and Kinoshita, 1976.
1963	October 5	1	East rift	3.4	6.9	Moore and Koyanagi, 1969.
1965	March 5	10	East rift (Makaopuhi, Napau)	7.8	18.0	Wright and others, 1968.
1965	December 24	1	East rift (Alae and vicinity)	.6	.9	Fiske and Koyanagi, 1968.
1967	November 5	251	Halemaumau	.65	84.1	Kinoshita and others, 1969.
1968	August 22	5	East rift	.03	.04	Jackson and others, 1975.
1968	October 7	15	-- do	2.1	7.0	Do.
1969	February 22	6	-- do	6.0	17.0	Swanson and others, 1976b.
1969	May 24	875	East rift (Mauna Ulu)	50.0	185.0	Swanson and others, 1971, 1979; Peterson and others, 1976, p. 647–648.
1971	August 14	1	Caldera	2.0	10.0	Peterson and others, 1976, p. 649–650; Duffield and others, 1982.
1971	September 24	5	Halemaumau, caldera, southwest rift	4.0	8.0	Peterson and others, 1976, p. 650; Duffield and others, 1982.
1972	February 3	455	East rift (Mauna Ulu)	35.0	125.0	Peterson and others, 1976, p. 651–652; Tilling and others, chapter 16.
1973	May 5	1	East rift (Pauahi, Hiiaka)	.14	1.0	Peterson and others, 1976, p. 651–652; Tilling and others, chapter 16.
1973	May 7	187	East rift (Mauna Ulu)	.5	2.5	Peterson and others, 1976, p. 652; Tilling and others, chapter 16.
1973	November 10	30	East rift (Pauahi and vicinity)	1.5	3.0	Peterson and others, 1976, p. 652–653; Tilling and others, chapter 16.

TABLE 7.3.—*Historical eruptions of Kilauea through May 1985*—Continued

Date eruption began Year	Month and day	Duration (days)	Location of major vent(s)	Approximate area (km^2)	Approximate volume ($m^3 \times 10^6$)	References
1973	December 12	222	East rift (Mauna Ulu)	8.0	30.0	Peterson and others, 1976, p. 653–654; Tilling and others, chapter 16.
1974	July 19	3	Caldera, Keanakakoi, and vicinity)	3.2	10.0	Peterson and others, 1976, p. 656; Lockwood and others, chapter 19.
1974	September 19	1	Halemaumau, caldera	1.1	11.0	Do.
1974	December 31	1	Southwest rift, Koae fault system	7.5	15.0	Do.
1975	November 29	1	Halemaumau, caldera	---	.25	Tilling and others, 1976, p. 15–17.
1977	September 12	20	East rift	8.0	35.0	Moore and others, 1980.
1979	November 16	1	East rift (Pauahi and vicinity)	.17	.7	Banks and others, 1981.
1980	March 11	1	East rift (near Mauna Ulu)	.0001	.000003	
1982	April 30	1	Halemaumau, caldera	.25	.5	Banks and others, 1983.
1982	September 23	1	South outer caldera	.75	4.0	Banks and others, 1983.
1983	January 3	continuing (August 1986)	East rift, Puu Oo	40 (approx)	350 (approx)	Wolfe and others, chapter 17.

of the same basic limitations as did that of Stearns (1946). New facts, as they become available, will inevitably modify current concepts, and we hope the progress will be at a rate such that this new scheme will require early revision.

We propose the following scheme of evolution for Hawaiian volcanoes (see fig. 7.9 and table 7.5)

1. Initial stage. Although little known, products apparently include a variety of differentiated, alkalic-type lavas. Calderas are possible.
2. Shield-building stage. Products are tholeiitic basalt and tholeiitic picrite, and major growth of the shield volcano occurs. Eruptions are frequent and voluminous. Three substages are recognized according to physical environment:
   a. Submarine substage; dominantly pillow lava and derivatives, relatively steep slopes.
   b. Sea-level substage; development of hyaloclastite rocks chiefly by explosive interaction between molten lava and seawater and by wave abrasion.
   c. Subaerial substage; pahoehoe and aa build gently sloping shield-shaped edifice; small percentage of tephra.

   Calderas and pit craters may form and be filled repeatedly during any of these substages.
3. Capping stage. Magma becomes differentiated to yield alkalic basalt and other alkalic rocks. Eruptions become less frequent, lava becomes more viscous and is interspersed with explosive products, and a steeper sided cap is built. Any existing caldera is filled. Eruptions decline and finally end.
4. Erosional stage. Erosion by streams and waves carves valleys, canyons, and seacliffs. Although erosion operates during stages (2) and (3), affecting any portion of the volcano not frequently covered by new eruptive products, it becomes the dominant process when eruptions end. Corals grow in the shallow water around the islands and may build large reefs when undisturbed by new lava.
5. Renewed volcanism stage. After long quiescence of hundreds of thousands to perhaps more than a million years, alkalic basalt and more highly differentiated lavas, such as basanite and nephelinite, may erupt intermittently, both as lava and tephra, through a span of perhaps thousands of years. Erosion and reef building continue in unaffected areas.
6. Atoll stage. After stream and wave erosion, coupled with subsidence induced by volcanic loading, have reduced the volcano to sea level, the former island typically is encircled by coral reefs. If subsidence continues, coral may build an edifice atop the eroded volcanic rock to thicknesses of hundreds of meters.
7. Late seamount stage. Rate of regional subsidence eventually exceeds rate of reef building; island sinks below sea level to become a seamount; pelagic sediments mantle edifice, which may survive quietly for millions of years.

Each Hawaiian volcano begins growing in a deep-ocean environment, but only a single example, Loihi, has provided clues to the composition and characteristics of the lava of the deep-sea stage. Loihi is as yet little explored, but it is already a large volcano, rising at least 3,000 m above its base. A wealth of petrologic information has been extracted from the dredged samples from Loihi, an innovative petrogenetic evolution has been suggested (Frey and Clague, 1983), and it is tempting to assume that all or most Hawaiian volcanoes have undergone this same petrogenesis. The assumption is reasonable, but the characteristics of later stages are all derived from the study of several or many volcanoes. Hence, until rocks similar to those of Loihi are found at other new seamounts or are encountered by deep drilling into the core of older volcanoes, the details and implications of stage (1) should be considered provisional.

Stage 1 begins with fissures or single vents erupting lava onto the ocean floor. Repeated flows build a submarine edifice (fig. 7.9), which consists mostly of pillow lava. If of alkalic composition, the edifice may have sides that are quite steep; the bathymetry of Loihi (Malahoff, chapter 6; Malahoff and others, 1982) shows some slopes approaching 45°. The first embryonic volcano in a region would grow independently of any influence by neighboring edifices. However, when one or more additional volcanoes develop nearby,

TABLE 7.4.—*Historical eruptions of Mauna Loa through 1985*

[Dashes (---), no data; query (?), questionable data]

Date eruption began Year	Month and day	Duration (days)	Location of major vent(s)	Approximate area (km^2)	Approximate volume ($m^3 \times 10^6$)	References
1832	June 20	21 (?)	Caldera	---	---	Stearns and Macdonald, 1946, p. 79.
1843	January 9	95	Northeast rift	53	191	Brigham, 1909, p. 63–65; Hitchcock, 1909, p. 84–85.
1849	May 15	15	Caldera	---	---	Coan, 1851; Brigham, 1909, p. 65; Hitchcock, 1909, p. 85
1851	August 8	21	-- do	18	69	Brigham, 1909, p. 65; Hitchcock, 1909, p. 85–86.
1852	February 17	21	Caldera, northeast rift	28	107	Coan, 1852; Brigham, 1909, p. 65–68; Hitchcock, 1909, p. 86–94.
1855	August 11	450	Northeast rift	31	115	Brigham, 1909, p. 68–71; Hitchcock, 1909, p. 94–100.
1859	January 23	300	North flank	85	459	Davis, 1859; Dana, 1859, 1860; Brigham, 1909, p. 75–80; Green, 1887; Hitchcock, 1909, p. 100–104.
1865	December 30	120	Caldera	---	---	Hitchcock, 1909, p. 104.
1868	March 27	16	Southwest rift	24	145	Coan, 1869; Brigham, 1909, p. 100–116; Hitchcock, 1909, p. 104–111; Moore and Ault, 1965, p. 5–7; Fisher, 1968.
1871	August 1	30	Caldera	---	---	Coan, 1871, p. 456.
1872	August 10	60	-- do	---	---	Brigham, 1909, p. 125; Hitchcock, 1909, p. 111–112.
1873	January 6	2 (?)	-- do	---	---	Brigham, 1909, p. 126; Hitchcock, 1909, p. 112–114.
1873	April 20	547	-- do	---	---	Brigham, 1909, p. 122–127; Hitchcock, 1909, p. 114–115.
1875	January 10	30	-- do	---	---	Brigham, 1909, p. 127; Hitchcock, 1909, p. 115; Coan, 1877.
1875	August 11	7	-- do	---	---	Do.
1876	February 13	1	-- do	---	---	Brigham, 1909, p. 127; Coan, 1877.
1877	February 14	11	Caldera, west flank (offshore)	---	---	Brigham, 1909, 127–128; Hitchcock, 1909, p. 115–116; Coan, 1877.
1880	May 1	6	Caldera	---	---	Brigham, 1909, p. 133, 145; Hitchcock, 1909, p. 116.
1880	November 1	280	Northeast rift	62	230	Brigham, 1909, p. 145–155; Hitchcock, 1909, p. 116–119.
1887	January 16	10	Southwest rift	29	230	Brigham, 1909, p. 165–168; Hitchcock, 1909, p. 123–127.
1892	November 30	3	Caldera	---	---	Brigham, 1909, p. 185.
1896	April 21	16	-- do	---	---	Brigham, 1909, p. 192–196; Hitchcock, 1909, p. 128–130.
1899	July 4	23	Caldera, northeast rift	42	153	Brigham, 1909, p. 196–199; Hitchcock, 1909, p. 132–138.
1903	October 6	60	Caldera	---	---	Brigham, 1909, p. 202–204; Hitchcock, 1909, p. 138–139.
1907	January 9	15	Caldera, southwest rift	21	76	Brigham, 1909, p. 206–209; Hitchcock, 1909, p. 142–146.
1914	November 25	48	Caldera	---	---	Jaggar, 1947, p. 99.
1916	May 19	14	Southwest rift	17	61	Jaggar, 1947, p. 104.
1919	September 26	42	Caldera, southwest rift	24	268	Jaggar, 1919, 1947, p. 125–133; Moore and Ault, 1965, p. 7.
1926	April 10	15	-- do	35	115	Jaggar, 1926, 1947, p. 171–173.
1933	December 2	17	Caldera	5	76	Jaggar, 1947, p. 195–196.
1935	November 21	42	Caldera, northeast rift	36	122	Jaggar, 1947, p. 197–200.
1940	April 7	133	Caldera	10	76	Macdonald, 1954; Macdonald and Abbott, 1970, p. 57–60.
1942	April 26	15	Caldera, northeast rift	28	76	Macdonald, 1954; Macdonald and Abbott, 1970, p. 60–65.
1949	January 6	145	Caldera	15	59	Macdonald and Orr, 1950; Finch and Macdonald, 1951; Macdonald and Abbott, 1970, p. 65–67.
1950	June 1	23	Southwest	91	460	Finch and Macdonald, 1953; Macdonald, 1954; Macdonald and Abbott, 1970, p. 9–11.
1975	July 5	1	Caldera, southwest and northeast rifts	14	30	Lockwood and others, chapter 19, 1976.
1984	March 25	22	Caldera, southwest rift, and, primarily, northeast rift	48	220	Lockwood and others, chapter 19, 1985.

the flows from two or more sources begin to interfinger, and the presence of each volcano would influence the path of flows from its neighbor. Linear rift zones develop, with their orientations determined by stress fields influenced both by regional tectonics and local gravitational forces (Fiske and Jackson, 1972).

The shield-building stage (2) includes the principal growth of the volcano; products consist almost exclusively of tholeiitic basalt and tholeiitic picrite (olivine-rich tholeiite). By far the greatest proportion of Hawaiian volcanoes consists of tholeiite erupted during the shield-building stage (fig. 7.9, table 7.5). Three substages have been designated submarine (2a), sea level (2b), and subaerial (2c); the behavior of the erupted products and their physical character is largely determined by which of these three environments they encounter.

The submarine substage (2a) involves the repeated voluminous extrusion of tholeiite, which assumes the form of pillow lava;

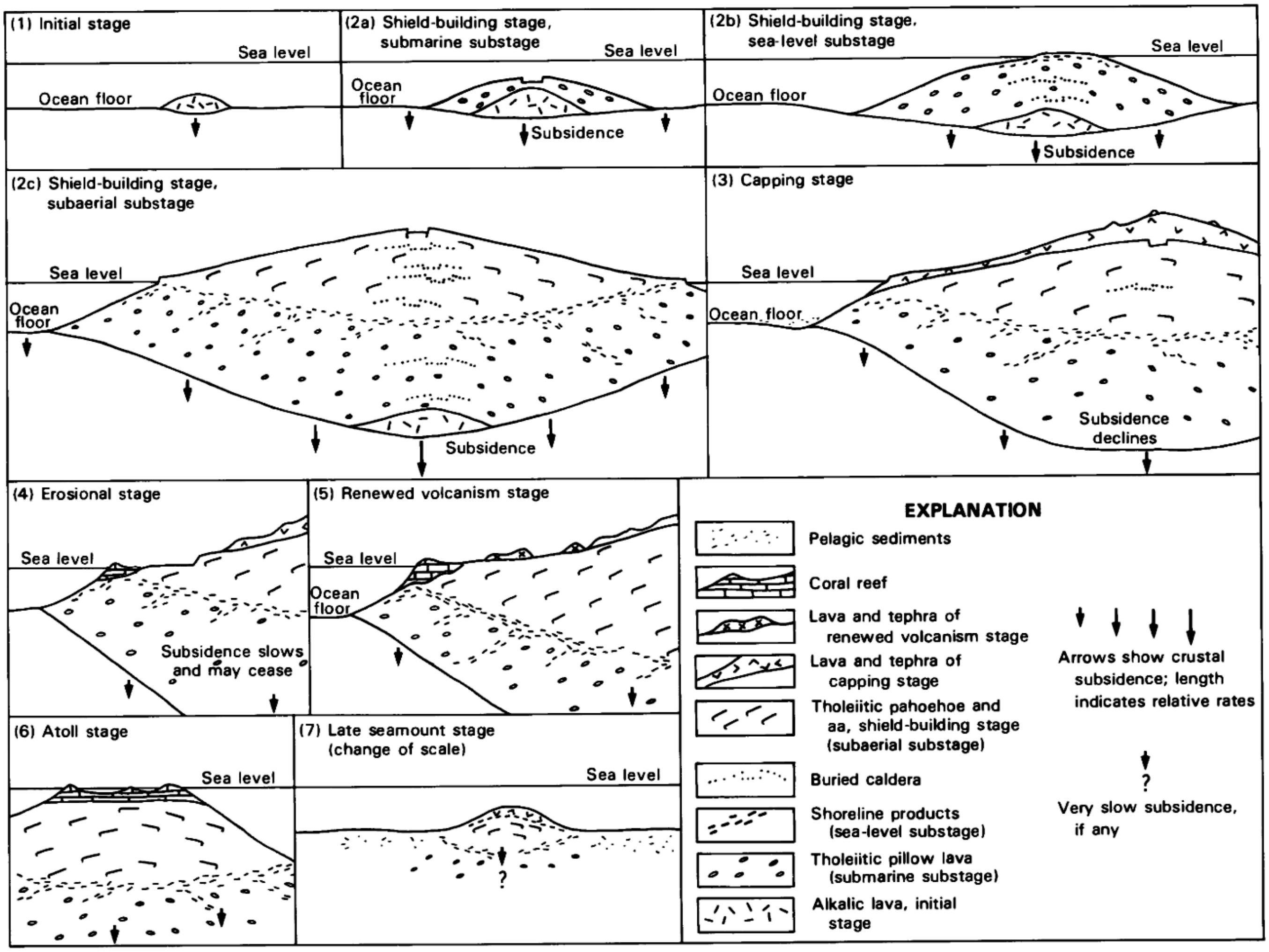

FIGURE 7.9.—Diagrams showing successive stages in evolution of a Hawaiian volcano as proposed in this paper. Changes between stages normally are transitional and gradational. For simplicity, feeder conduits and rift zones are omitted. Substantial crustal subsidence caused by volcanic loading occurs throughout growth stages (1) through (3); subsequent sea-level changes may be sporadic, but net subsidence continues into stage (7). Vertical exaggeration varies from approximately 2× to approximately 4×. Only stages (1) through (4) are represented on Hawaii. See text for additional details.

countless repeated flows build a submarine shield volcano. Lava issues from both summit vents and rift zones, and submarine eruptions probably exhibit as wide a variety of flow behavior as do subaerial eruptions, except that below a few hundred meters depth the pressure is sufficient to inhibit explosive activity, and any vesicles are only of microscopic size. Slopes of the edifice are generally 10° to 20°. The crust beneath the volcano subsides during rapid growth and volcanic loading; thus the length of time required for the summit to reach sea level is longer than previously thought, perhaps approaching a million years (Moore, chapter 2).

As the summit of the growing submarine shield approaches sea level, the sea-level substage (2b) begins. The hydrostatic head declines enough to allow the ocean water to boil when encountered by vesiculating molten lava. The abrupt production of steam disrupts the lava, sometimes explosively, and it is shattered to form tephra and hyaloclastite material (Moore and Fiske, 1969). As the process continues, a broad mound of mixed tephra and lava eventually emerges above sea level. Waves immediately begin to erode the tephra and fragment the lava, and initially the new island may be transitory. But if the supply of new material is steady and sufficiently large, the volcanic pile grows fast enough to keep ahead of wave erosion, and the new island enlarges. When the vent is sufficiently protected from sea water, explosions decline and coherent flows form a resistant veneer over the fragmental material, reducing the rate of wave erosion. The island of Surtsey, south of Iceland, is a well-observed example of the process by which a basaltic volcano initially emerges above the sea (Thorarinsson, 1967). Although the process has not been observed in Hawaii, basaltic volcanoes there would

TABLE 7.5.—*Revised evolutionary scheme for Hawaiian volcanoes*

Stage	Dominant composition of magma	Dominant geologic processes and characteristics[1]
(1) Initial	Alkalic basalt, basanite, transitional basalt	Initial activity of new volcano; rates and frequency of eruption and duration of stage not known; edifice may be steep sided (because only a single example is recognized, this stage is considered provisional).
(2) Shield-building	Tholeiitic basalt, tholeiitic picrite	Frequent voluminous eruptions from central vent and rift zones, historic examples suggest eruptive rates of 1–3 km³/100 yr, frequency about 5–50 eruptions/100 yr; shield-shaped edifice built; caldera may form and be refilled repeatedly during any substage.
(2a) Submarine	-- do ----------------	Products pillow lava and pillow fragments; moderately steeply sloping edifice.
(2b) Sea level	-- do ----------------	Products hyaloclastites—the result of explosive interaction between sea water and molten lava, and wave abrasion.
(2c) Subaerial	-- do ----------------	Products chiefly pahoehoe and aa lava flows, interspersed with sporadic tephra produced by occasional explosions; dominantly fluid lava builds gently sloping edifice; processes of 2a and 2b continue.
(3) Capping	Alkalic basalt, transitional basalt, other alkalic rocks[2]	Products initially pahoehoe and aa lava flows, increasing proportions of tephra-built cinder cones, gradual or abrupt change to smaller briefer eruptions; increasing lava viscosity (block flows); declining eruptive rates and frequency of eruptions, eventually at intervals exceeding 10^3 yr; capping structure steeper sided than stage 2c.
(4) Erosional	None	Lack of eruptions allows fluvial and marine erosion to carve valleys, canyons, cliffs, and so on; reefs may develop along some shorelines (erosion operates during all stages, but effects offset by repeated eruptions).
(5) Renewed volcanism	Alkalic basalt, basanite, nephelinite, nephiline melilitite	Sporadic eruptions, generally from vents not related to central conduit or rift zones, commonly explosive though some are effusive. Eruptions are of low volume and widely spaced in time. Erosion and reef building continue.
(6) Atoll	None	Abetted by regional subsidence, fluvial and marine erosion reduce volcano to sea level. Reef building continues, may form ring-shaped group of islands with interior lagoon.
(7) Late seamount	None	Rate of regional subsidence eventually exceeds rate of reef building and island sinks below sea level to become a seamount; gradually mantled by pelagic sediments; subdued edifice may survive for millions of years.

[1]In addition to processes listed, regional crustal subsidence caused by weight of growing volcanoes is nearly continuous, resulting in apparent rise in sea level. Episodes of glaciation cause a worldwide drop in sea level, temporarily offsetting steady regional subsidence.
[2]Other alkalic rocks may include hawaiite, mugearite, benmoreite, ankaramite, trachyte.

presumably emerge above the ocean in a like manner. The zone of tephra, fragmental lava, and hyaloclastite forms a distinctive horizon marking the transition from submarine to subaerial lava (Moore and Fiske, 1969). The behavior of lava at and below sea level was further reviewed above in the section "Submarine Investigations."

Once an island is established, the subaerial substage (2c) begins, which involves further growth of the shield by continued eruptions. The lava issues both from central vents and rift zones radial to the summit, and in composition the lava continues to be tholeiitic basalt. Slopes are generally from 3° to 10°, and they contrast distinctly with the steeper submarine slopes. Rate of growth is rapid, demonstrated by a general lack of both erosion and soils between successive flows. This substage is exemplified by frequent and well documented eruptions of Kilauea and Mauna Loa. As the subaerial shield grows, the processes of substages 2a and 2b continue below and at sea level as the volcano expands outward. Crustal subsidence continues (Moore, chapter 2), so that much of the subaerially erupted lava becomes part of the submarine edifice, and the hyaloclastite horizon assumes a broad, sagging profile (fig. 7.9). Calderas may form and be filled repeatedly throughout the tholeiitic lava stage.

The capping stage (3) begins as the magma eventually differentiates to yield alkalic basalt; at some volcanoes, lava transitional between tholeiitic and alkalic basalt is erupted (fig. 7.9, table 7.5). If a caldera is present, lava that fills it may be either tholeiite, transitional lava, or alkalic basalt. There is no theoretical reason why a caldera could not form during stage 3; calderas do occur in volcanoes of alkalic basaltic composition elsewhere in the world. However, they have not been observed to form during this stage in Hawaii, and in view of the declining volume rate of eruption characteristic of stage 3, caldera formation seems highly unlikely. With the change in composition, explosive eruptions become more common, and a steeper sided cap with slopes of as much as 20° is built over the shield. Differentiation may proceed further to yield one or more of the following: hawaiite, mugearite, benmoreite, trachyte, and ankaramite. Alkalic basalt, like tholeiite, forms pahoehoe and aa; the more differentiated lavas become increasingly viscous and may form block lava. Eruptions gradually become separated by progressively longer time intervals and finally end. Subsequent evolution of the volcanoes through the erosional stage (4), renewed volcanism stage (5), atoll stage (6), and late seamount stage (7) are briefly reviewed above, illustrated in figure 7.9, and outlined in table 7.5.

Of the volcanoes of Hawaii, Loihi seems to be at the end of stage 1, entering into stage 2a; Kilauea and Mauna Loa are in stage 2c; Hualalai is in stage 3; Mauna Kea is further along in stage 3, perhaps very late in the stage, and the processes of stage 4 are becoming dominant; and Kohala is in stage 4. None of these volcanoes has progressed beyond stage 4; the volcanoes of the other islands to the northwest are in various parts of stages 4 and 5, whereas stages 6 and 7 are represented by atolls, islets, and seamounts along the Hawaiian Ridge northwest of the main group of islands. Our stages 1, 2, 3, and 5 correspond to the four stages defined by Clague and Dalrymple (chapter 1, part I), although they are designated by different terms.

PETROLOGIC HISTORY OF INDIVIDUAL VOLCANOES

Though the volcanoes of Hawaii are broadly similar to one another in certain respects, each has achieved a specific position within the hierarchy of growth stages by means of an individual course of petrologic development. Each volcano is basically a tholeiitic shield, but Kohala, Mauna Kea, and Hualalai Volcanoes have passed into or beyond the capping stage (3), whereas Mauna Loa and Kilauea are in the subaerial part of the shield-building stage (2c). Loihi cannot yet be termed a tholeiitic shield, though it appears to have completed the initial stage (1) and is entering the submarine part of the shield-building stage (2a). Among the volcanoes with alkalic caps, tholeiitic lavas of Kohala and Mauna Kea are exposed in a few canyons on the Hamakua coast, whereas Hualalai tholeiites are not exposed on the subaerial surface but have been found in a few water wells and along the submarine extension of the northwest rift zone (Clague, 1982).

The petrologic development is summarized here by showing (1) chemical variations and similarities among tholeiitic and alkalic basalts of the five island volcanoes plus Loihi; (2) differentiation processes by which basaltic magma produces rocks of other compositions; and (3) effects of olivine control on related lavas. To illustrate these processes we have selected five basic variation diagrams as follows: $Na_2O + K_2O$ vs. SiO_2 (fig. 7.10), CaO vs. SiO_2 (fig. 7.11), CaO vs. MgO (fig. 7.12), TiO_2 vs. MgO (fig. 7.13), and Na_2O vs. MgO (fig. 7.14). These diagrams are derived from 834 chemical analyses of rocks from Hawaii, distributed among the volcanoes as follows: Kohala, 36 analyses; Mauna Kea, 36; Hualalai, 293; Mauna Loa, 117; Kilauea, 340; Loihi, 12. Most analyses are from references listed in table 7.6; some are unpublished data of E.D. Jackson (Hualalai), T.L. Wright (Hualalai), and R.B. Moore (Hualalai and Kilauea).

In spite of documented long-term storage of Hawaiian tholeiitic magma in rift zone reservoirs, fractionation of such magma has rarely produced compositions more silicic than basalt (boundary at 52 percent SiO_2). The sole known exception is the Yellow Cone scoria (Kilauea southwest rift zone) with 55 percent SiO_2, which was produced by mixing of a differentiate with 60 percent SiO_2 and 2 percent MgO with a more olivine-rich magma (Wright and Fiske, 1971). Otherwise, andesitic or more silicic compositions of tholeiitic parentage are unknown on the Island of Hawaii, although rhyodacite occurs on Oahu (Macdonald and others, 1983).

Most of the subaerial part of Kohala and Mauna Kea and all of Hualalai are composed of alkali olivine basalt and its differentiates, and the average recurrence interval for eruptions on Hualalai in the Holocene has been about 50 yr, as evidenced by radiocarbon age data (Moore and others, chapter 20). These facts suggest that alkali olivine basalt has been generated frequently during late Pleistocene and Holocene time. Fractionation of alkali olivine basalt magma has been extensive; the most differentiated rocks at each volcano include trachyte on Hualalai, benmoreite and trachyte on Kohala, and a single reported occurrence of mugearite on Mauna Kea.

Macdonald and Katsura (1964) described separate compositional fields for alkalic and tholeiitic basalts for the whole Hawaiian island chain, and these fields for the Island of Hawaii are illustrated in the alkali-silica variation diagrams of figure 7.10. A few basalts from each volcano straddle the boundary between the fields. The alkali-silica diagrams further show that slightly andesitic melts are the most SiO_2-rich erupted from the tholeiitic suite on the island, and that trachyte is the most silicic rock produced by fractionation of the alkalic suite.

The lime-silica variation diagrams (fig. 7.11) show rather diverse trends among the different volcanoes. Kohala, Mauna Kea, Hualalai, and Loihi illustrate the general alkalic trend of decreasing CaO with increasing SiO_2, whereas the data for the tholeiitic Mauna Loa and Kilauea volcanoes produce bell-shaped curves that peak at about 50–51 percent SiO_2.

The lime-magnesia variation diagrams (fig. 7.12) document the major role played by olivine in the tholeiitic suite for MgO content above about 6.8 percent (Powers, 1955; Wright 1971; Wright and others, 1975; Wright and Tilling, 1980). The change in slope of the curves below this point indicates departure from olivine control and the coprecipitation of pyroxenes and plagioclase. Curves for the alkalic rocks of Kohala, Mauna Kea, and Hualalai change slope at about the same point as those of the tholeiitic suite, suggesting that olivine-controlled fractionation is also important among some basaltic rocks of the alkalic suite. Wide scatter in most of the plots at contents of MgO greater than 6.8 percent indicates that considerable mixing of different batches of olivine-controlled magma, or differentiation involving phases in addition to olivine, has occurred in both suites (except on Mauna Loa; see Rhodes, 1983).

The titania-magnesia variation diagrams (fig. 7.13) show considerable scatter, even at relatively high MgO values, reflecting the effects of possible mixing of magma in shallow storage chambers as well as temporal variations at given contents of MgO. The reason for the change in slope among the alkalic rocks at 5–6 percent MgO, instead of the more usual 6.8 percent in the tholeiitic suite (Wright and Fiske, 1971), is not clear, but this change may reflect the accumulation of titaniferous clinopyroxene in magmas that have fractionated olivine nearly to its possible limit. Olivine-controlled lavas of Mauna Kea and Kilauea generally are higher in TiO_2 than those of the other volcanoes; the differences do not seem to be related to differences between the alkalic and tholeiitic suites.

The soda-magnesia variation diagram for all volcanoes together (fig. 7.14) shows again the importance of olivine-controlled fractionation and of mixing in shallow magma chambers (the part of the plotted data showing the latter is dominated by analyses of Kilauea rocks). The diagram also demonstrates the generally higher soda values in alkalic rocks (dominated by analyses of Hualalai rocks).

Relatively recent reports on the petrology of individual Hawaiian volcanoes and on models for generation of tholeiitic and alkalic magmas are given in table 7.6. These studies are summarized by Wright and Helz (chapter 23) and will be treated only briefly here. Most workers, beginning with Stearns and Macdonald (1946), have suggested that alkalic rocks are related to tholeiitic basalts either by protracted fractional crystallization of tholeiitic magma or by varying degrees of partial melting of the mantle source. This conclusion was based partly on the small volume of alkalic rocks compared to tholeiites and on field relations, notably the occurrence of basalts of transitional composition stratigraphically between tholeiitic and alkalic basalts on Kohala and Mauna Kea and on other islands in the Hawaiian Chain. More recently,

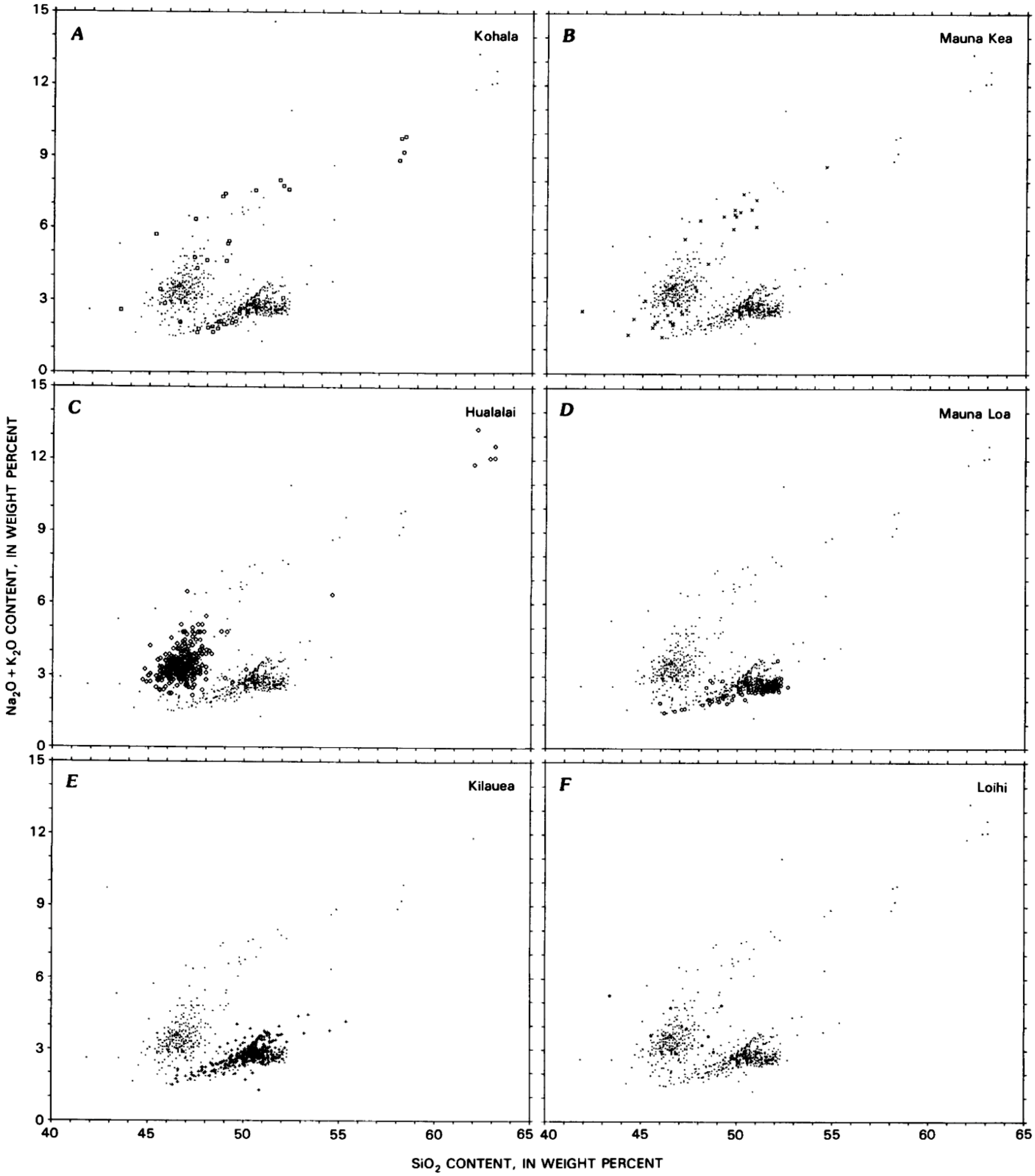

FIGURE 7.10.—Alkali-silica variation diagrams (Na_2O+K_2O vs. SiO_2) for volcanic rocks of Hawaii. ***A–F***, Plots for individual volcanoes as indicated. ***G***, Data for all six volcanoes combined. Individual diagrams show data for that volcano by heavy symbols and for comparison data for the other volcanoes by light dots. Analyses from published and unpublished sources.

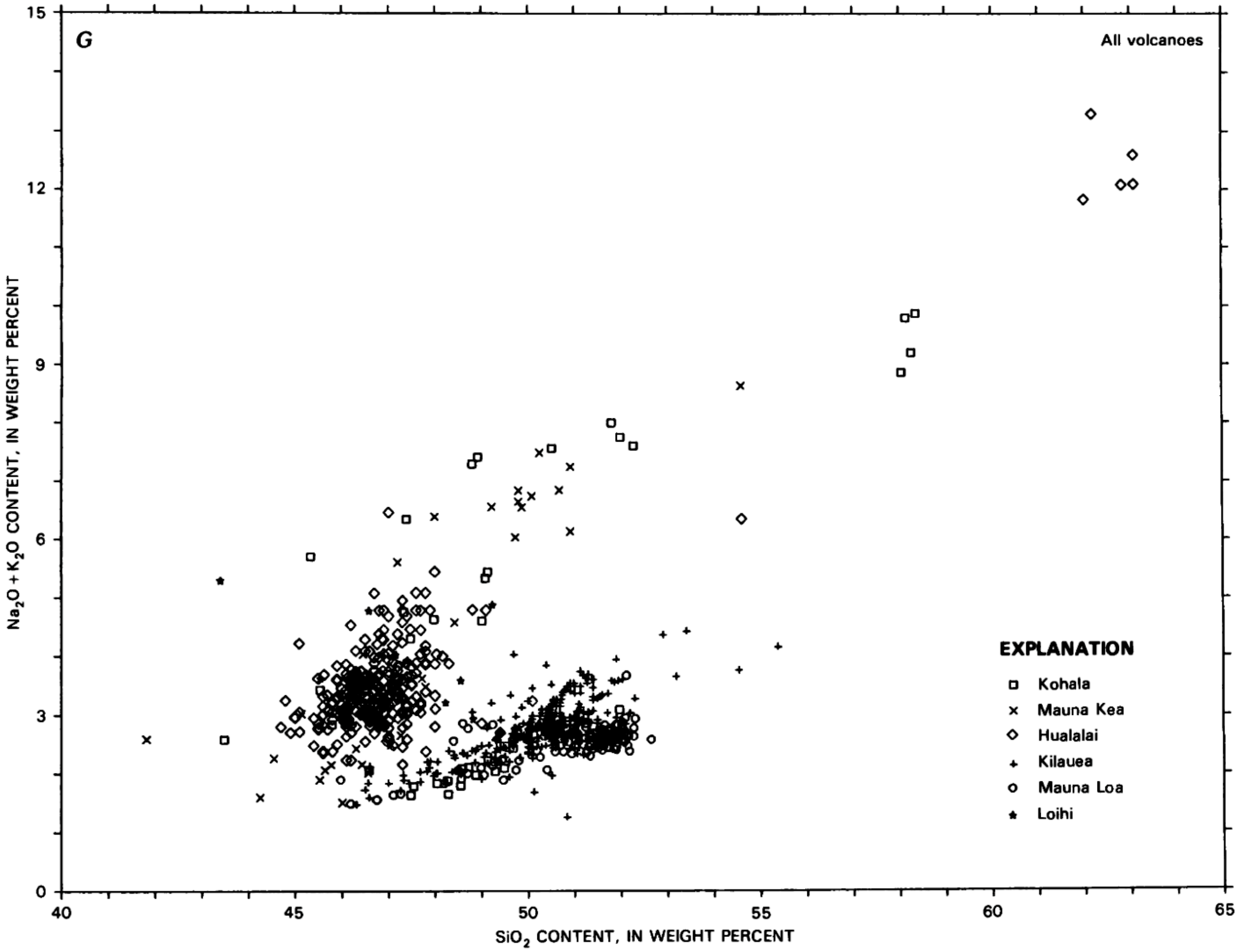

FIGURE 7.10.—Continued.

Lanphere and others (1980) concluded that alkalic and tholeiitic rocks are slightly different in terms of Rb and Sr abundances and isotopic compositions, suggesting intrinsic differences in mantle source regions. Lanphere (1983) has presented $^{87}Sr/^{86}Sr$ data for Loihi Seamount and concluded that the source materials for its divergent lavas are also isotopically distinct. Wright (1984) presented a metasomatic model for the origin of Hawaiian tholeiite that involves partial melting of a mantle source from which some midocean-ridge basaltic liquid has been removed and to which has been added a nephelinitic fluid, amphibole, apatite, iron sulfide, and magnetite/ilmenite.

KOHALA

Kohala is the longest inactive and likely the oldest volcano on the Island of Hawaii, although, as noted by Lipman (1980), ages of basalts in the Ninole Hills in the south flank of Mauna Loa are similar to those of the oldest dated Kohala lavas (0.7–0.45 Ma; see Evernden and others, 1964; Dalrymple, 1971).

The geology of Kohala was mapped in reconnaissance by Stearns and Macdonald (1946); detailed mapping by M.O. Garcia and S.C. Porter is in progress. Stearns and Macdonald recognized two major groups of volcanic units; they termed the older of these the Pololu Volcanic Series, which they considered to be Pliocene to early Pleistocene in age, and the younger the Hawi Volcanic Series, which they considered middle Pleistocene. These units have been renamed the Pololu Basalt and the Hawi Volcanics by Langenheim and Clague (chapter 1, part II). Subsequent K-Ar dating (McDougall, 1964; Dalrymple, 1971; McDougall and Swanson, 1972) has established a Pleistocene age (0.7–0.06 Ma) for all of the subaerially exposed part of Kohala. McDougall and Swanson (1972) concluded that the Pololu shield-building stage ended at

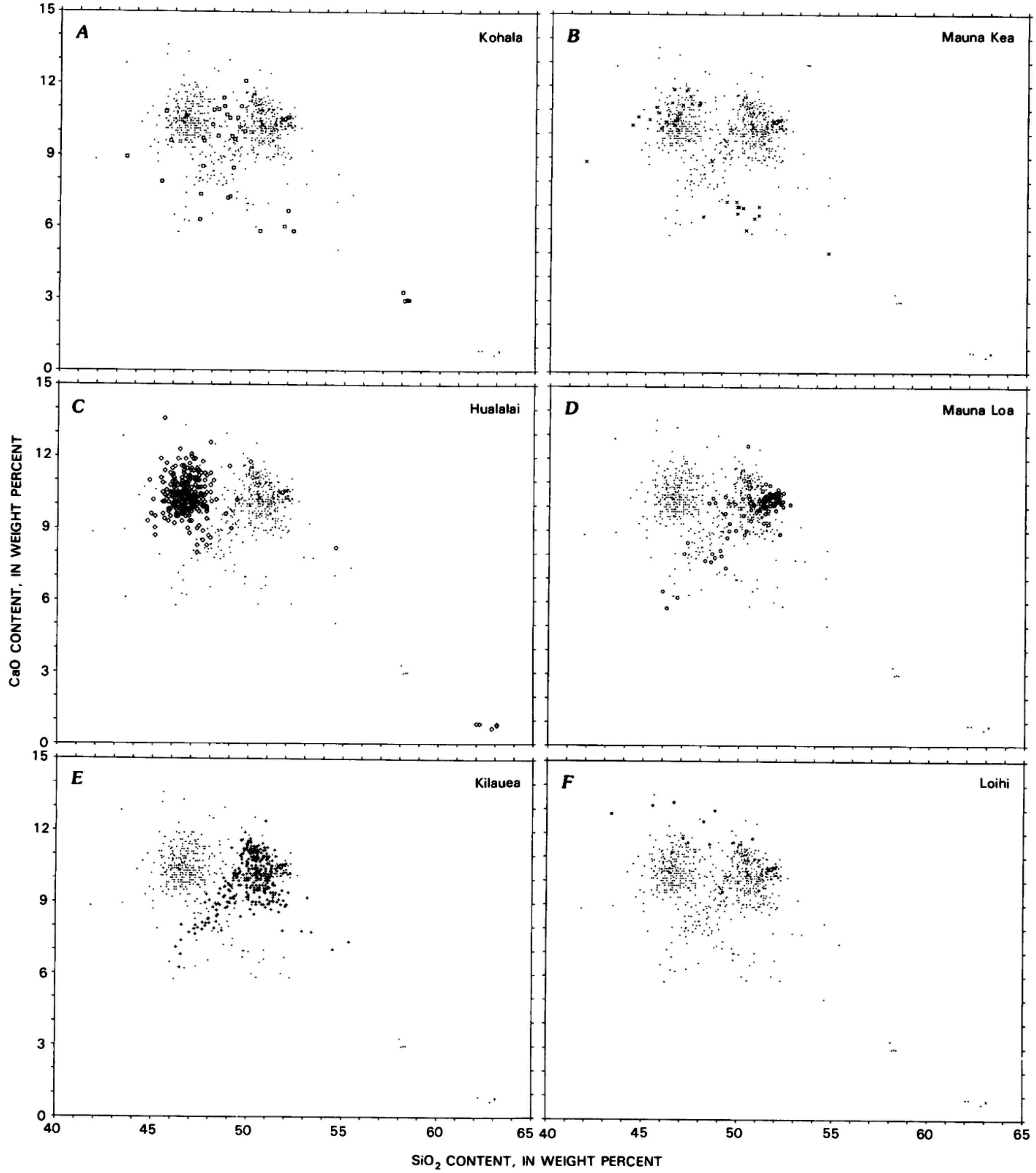

FIGURE 7.11.—Lime-silica variation diagrams (CaO vs. SiO_2) for volcanic rocks of Hawaii. ***A–F***, Plots for individual volcanoes, as indicated. ***G***, Data for all six volcanoes combined. Individual diagrams show data for that volcano by heavy symbols and for comparison data for other volcanoes by light dots. Analyses from published and unpublished sources.

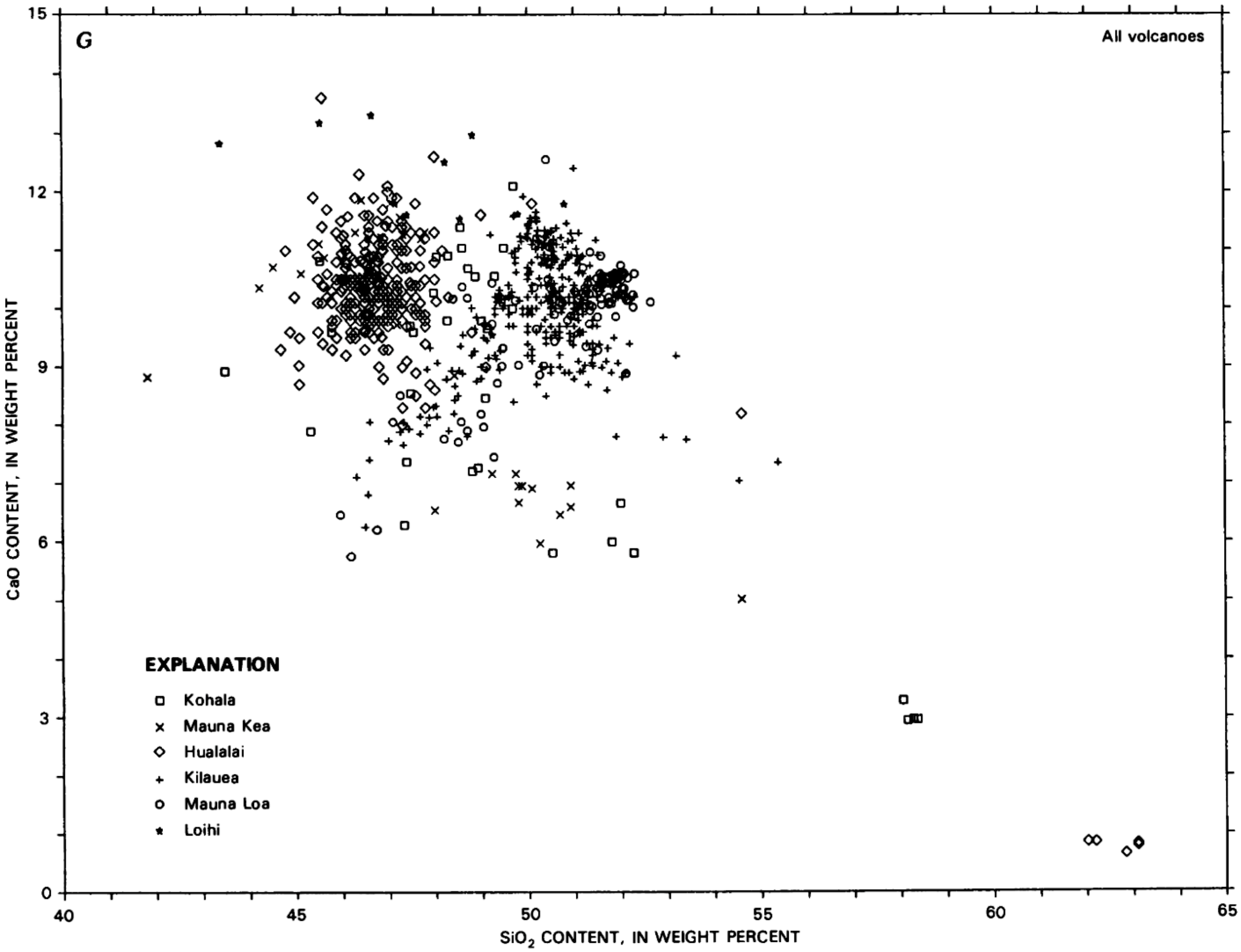

FIGURE 7.11.—Continued.

about 0.3 Ma and that the Hawi alkalic cap was formed by eruptions at 0.25–0.06 Ma (see fig. 7.4).

The lower part of the Pololu Basalt is tholeiitic (Macdonald and Katsura, 1964) and was extruded during the shield-building stage of the volcano; the younger volcanic materials are alkalic and characterized by larger proportions of intercalated cinders and ash. Variation diagrams (figures 7.10–7.14) suggest that some transitional basalts occur in the upper part of the Pololu Basalt.

The Hawi Volcanics is entirely alkalic and ranges in composition from alkali olivine basalt to benmoreite. Mugearites are particularly abundant, and more mafic rocks are rare. Feigenson and others (1983) report the occurrence of dunite xenoliths in some alkali basalt flows. Most of the Hawi vents are along Kohala's northwest-southeast-trending rift zone; the relation of this rift to the geometry of the tholeiitic shield is unknown, although probably the modern rift zone approximately coincides with the ancient one. A caldera that probably formed during Pololu time was buried by Hawi lavas (Stearns and Macdonald, 1946).

Variation diagrams (fig. 7.10–7.14) for Kohala rocks show that they generally are similar to rocks from Mauna Kea. Rocks of Kohala are somewhat more evolved, however; a single mugearite has been reported from Mauna Kea, whose subaerial lavas are dominated by hawaiite, ankaramite, and alkali olivine basalt.

The alkali-silica variation diagram for Kohala rocks (fig. 7.10*A*) shows the fields of tholeiitic and alkalic rocks and the differentiation products of alkali olivine basalt that include hawaiite, mugearite, and benmoreite. The lime-silica variation diagram for Kohala (fig. 7.11*A*) shows considerable scatter in the basalt range,

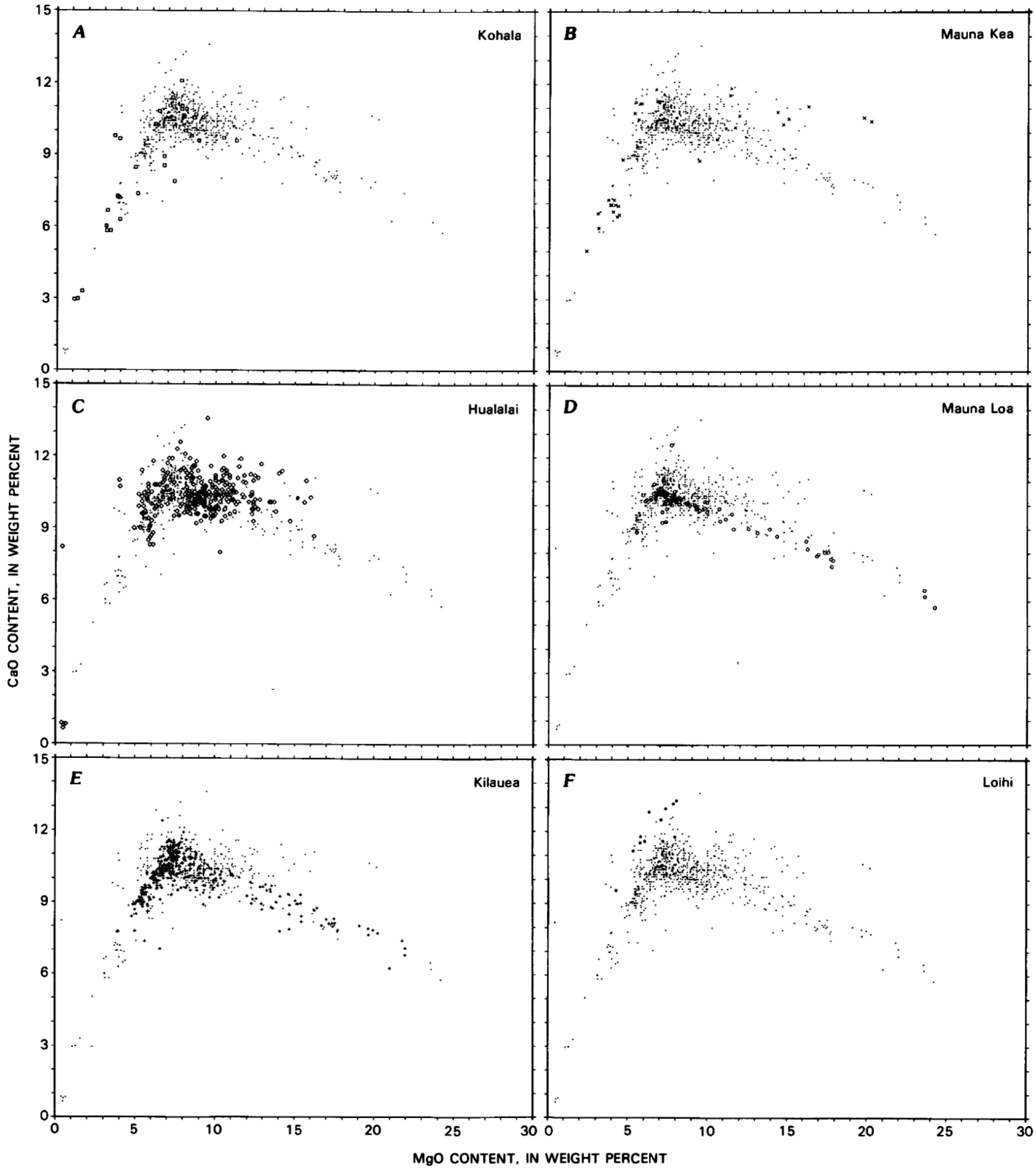

FIGURE 7.12.—Lime-magnesia variation diagrams (CaO vs. MgO) for volcanic rocks of Hawaii. ***A–F***, Plots for individual volcanoes, as indicated. ***G***, Data for all six volcanoes combined. Individual diagrams show data for that volcano by heavy symbols and for comparison data for other volcanoes by light dots. Analyses from published and unpublished sources.

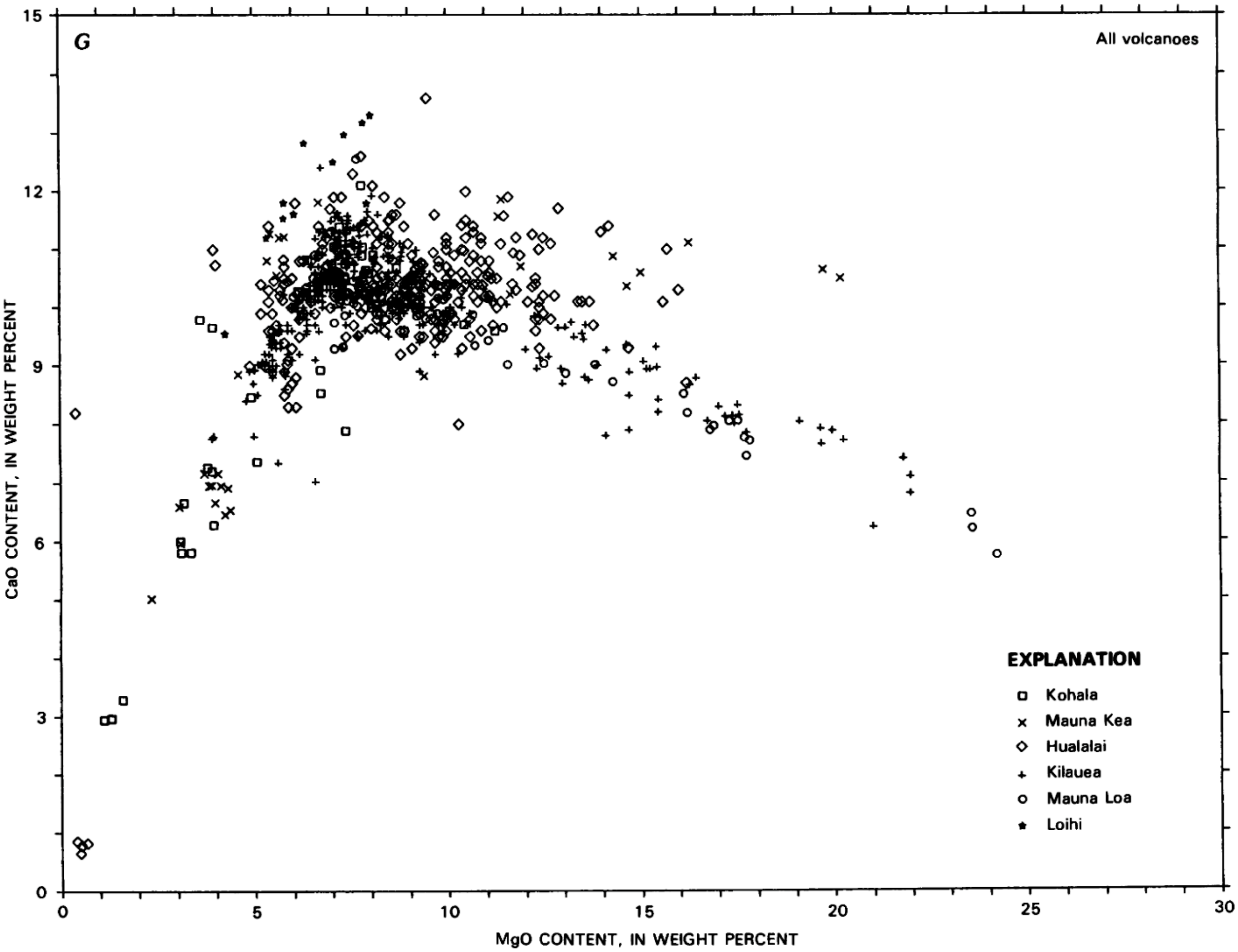

FIGURE 7.12.—Continued.

probably resulting from highly variable proportions of plagioclase and clinopyroxene phenocrysts. Mugearites and benmoreites of Kohala fall on a smooth trend. The lime-magnesia diagram (fig. 7.12 *A*) shows that Kohala tholeiites are similar to those from Hualalai, Mauna Loa, and Kilauea. The titania-magnesia diagram (fig. 7.13*A*) shows broad scatter among the Kohala rocks, suggesting that considerable mixing (Feigenson, 1984) and accumulation of Ti-rich phases (ilmenite, titanomagnetite, Ti-rich clinopyroxene) have occurred. Figure 7.14 (soda-magnesia diagram) further suggests that Kohala tholeiites are similar to those from Kilauea and Mauna Loa and that its alkalic rocks are generally similar to those from Hualalai and Mauna Kea.

MAUNA KEA

Mauna Kea has been inactive the second longest among volcanoes on the island of Hawaii. Some Mauna Kea lavas overlie rocks of Kohala on the east and south sides of Kohala; interlayering of lavas from the two sources likely occurs at depth. Stearns and Macdonald (1946) divided Mauna Kea lavas into the older Hamakua Volcanic Series (Pleistocene) and the younger Laupahoehoe Volcanic Series (Pleistocene and Holocene), now called the Hamakua Volcanics and Laupahoehoe Volcanics, respectively (fig. 7.4; Langenheim and Clague, chapter 1, part II). The two units locally are separated by as much as 5 m of weathered ash (originally called the Pahala Ash), most of which probably originated from proximal vents on Mauna Kea.

K-Ar ages reported by Porter and others (1977) range from 375 ± 50 ka to 270 ± 35 ka for the Hamakua Volcanics and 188 ± 15 ka to 54.9 ± 8.5 ka for the Laupahoehoe Volcanics. Radiocarbon ages by the same authors indicate that some Laupahoehoe lavas are as young as about 4.5 ka, and ash is as young as 3.6 ka (Porter, 1979b).

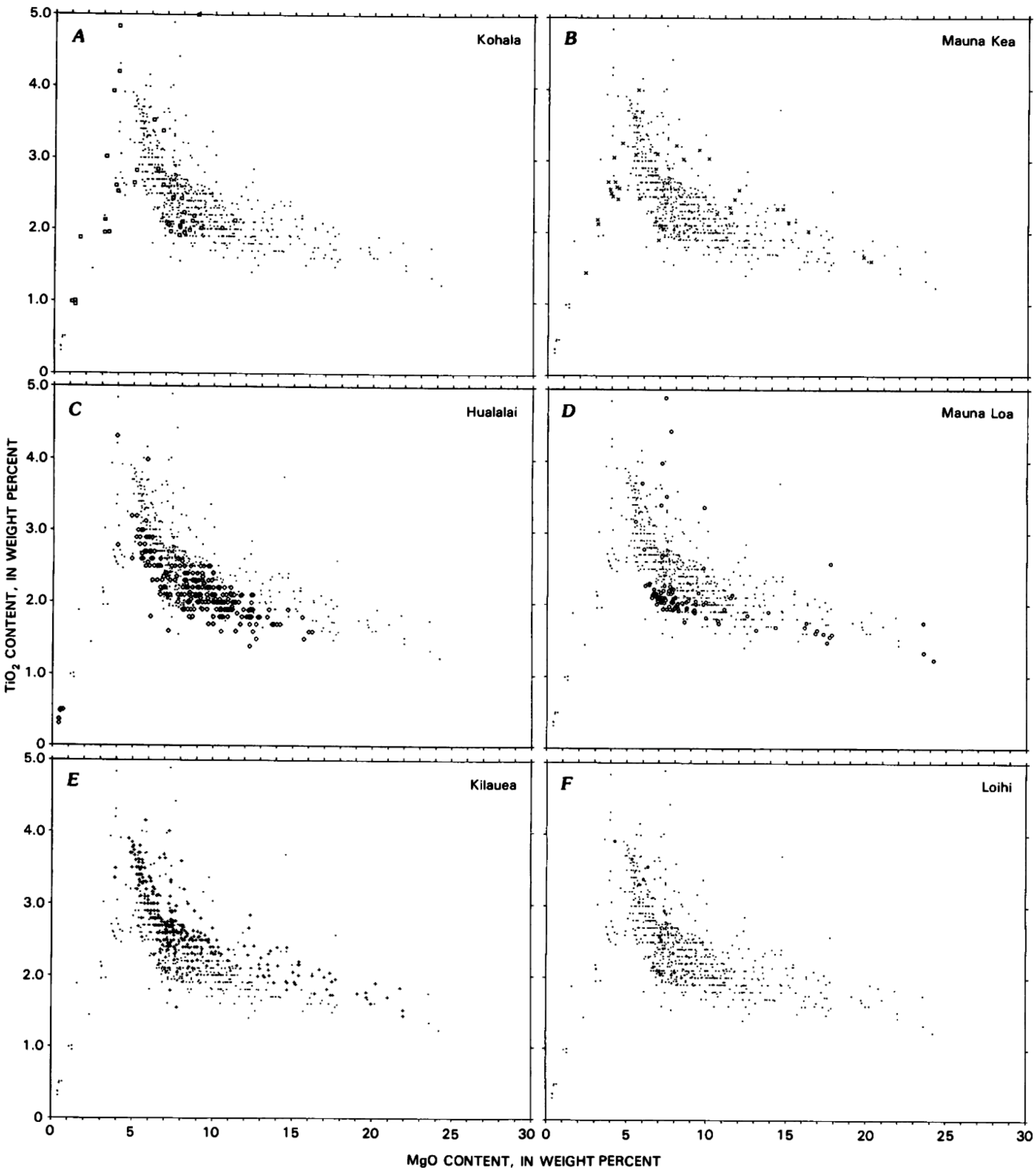

FIGURE 7.13.—Titania-magnesia variation diagrams (TiO_2 vs. MgO) for volcanic rocks of Hawaii. ***A–F***, Plots for individual volcanoes as indicated. ***G***, Data for all six volcanoes combined. Individual diagrams show data for that volcano by heavy symbols and for comparison data for volcanoes by light dots. Analyses from published and unpublished sources.

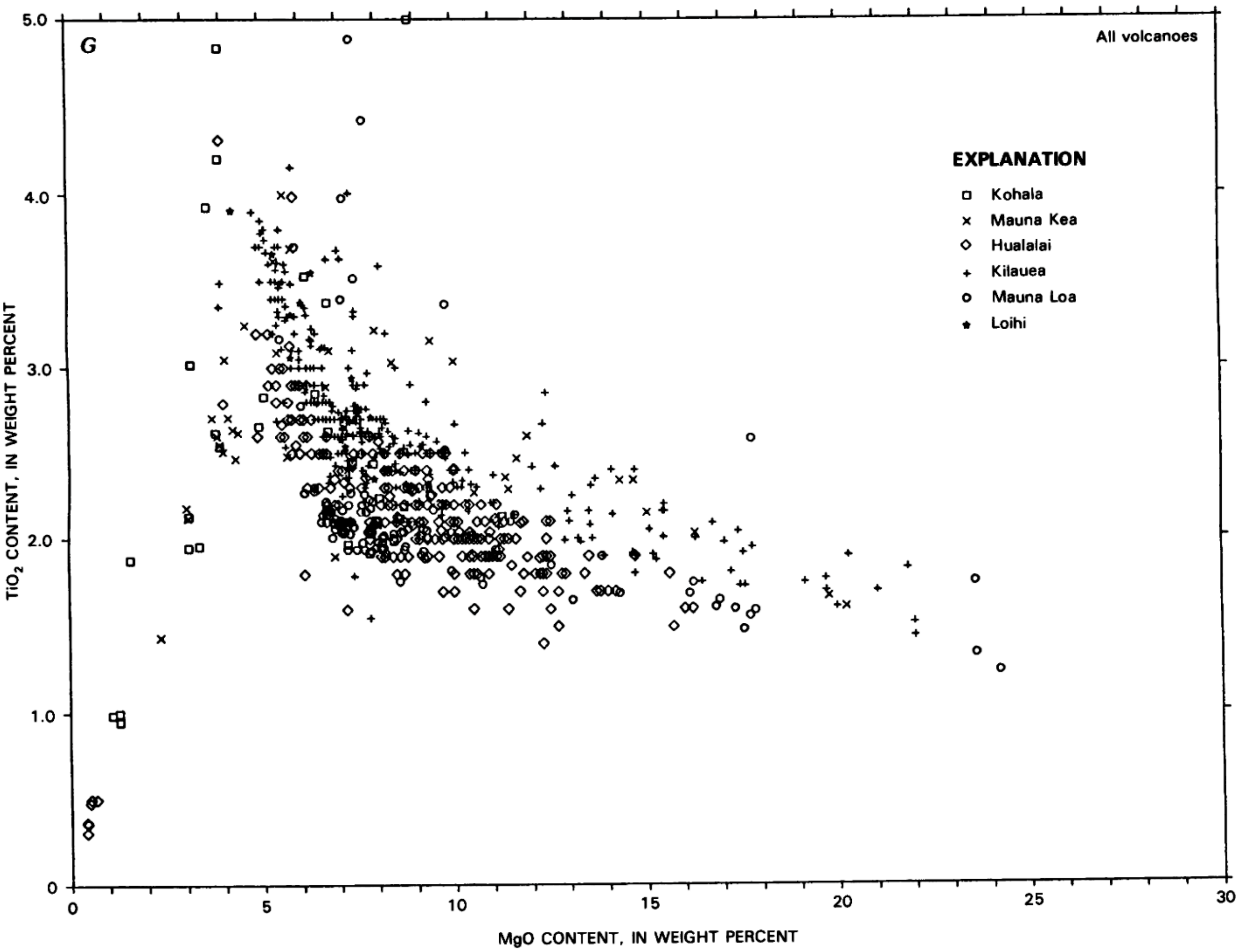

FIGURE 7.13.—Continued.

Tholeiitic basalts of the Hamakua Volcanics crop out only locally on the Hamakua (northeastern) coast of the island, where they commonly are interbedded with transitional and alkalic basalts (Macdonald and Katsura, 1964; Macdonald, 1968). The bulk of the subaerial part of the volcano, including all of the Laupahoehoe Volcanics, consists of transitional basalts, alkali olivine basalts, ankaramites, hawaiites, and a single known mugearite (Macdonald, 1968). Eruptions of alkali olivine basalt and derivative lavas produced cinder cones and lava flows (chiefly aa), widely distributed on the flanks and summit area of the volcano. Xenoliths of mafic and ultramafic rocks, commonly of cumulus origin, occur in several cones and flows (Jackson and others, 1982).

The early structural and eruptive history of Mauna Kea is conjectural, because alkalic lavas that constitute its cap have buried most structures. Porter (1972) recognized diffuse rift zones trending west, south-southeast, and east-northeast from an inferred buried caldera beneath the summit. It is not known whether these alignments of vents were inherited from the early tholeiitic, shield-building stage of the volcano.

As noted above, lavas of Mauna Kea are quite similar to, but generally less evolved than, those of Kohala (fig. 7.10–7.14). The alkali-silica variation diagram for Mauna Kea rocks (fig. 7.10*B*) indicates that virtually all analyzed lavas are alkalic. Fig. 7.11*B* shows that CaO decreases with increasing SiO_2, as with alkalic rocks from the other volcanoes. Wide scatter at the low-SiO_2 end suggests highly variable proportions of plagioclase and clinopyroxene phenocrysts. Figure 7.12*B* indicates that ankaramites from Mauna Kea with MgO greater than 11 percent are similar only to a few ankaramites from Hualalai. Fig. 7.13*B* shows that high-MgO Mauna Kea ankaramites and Kilauea tholeiites have similarly high

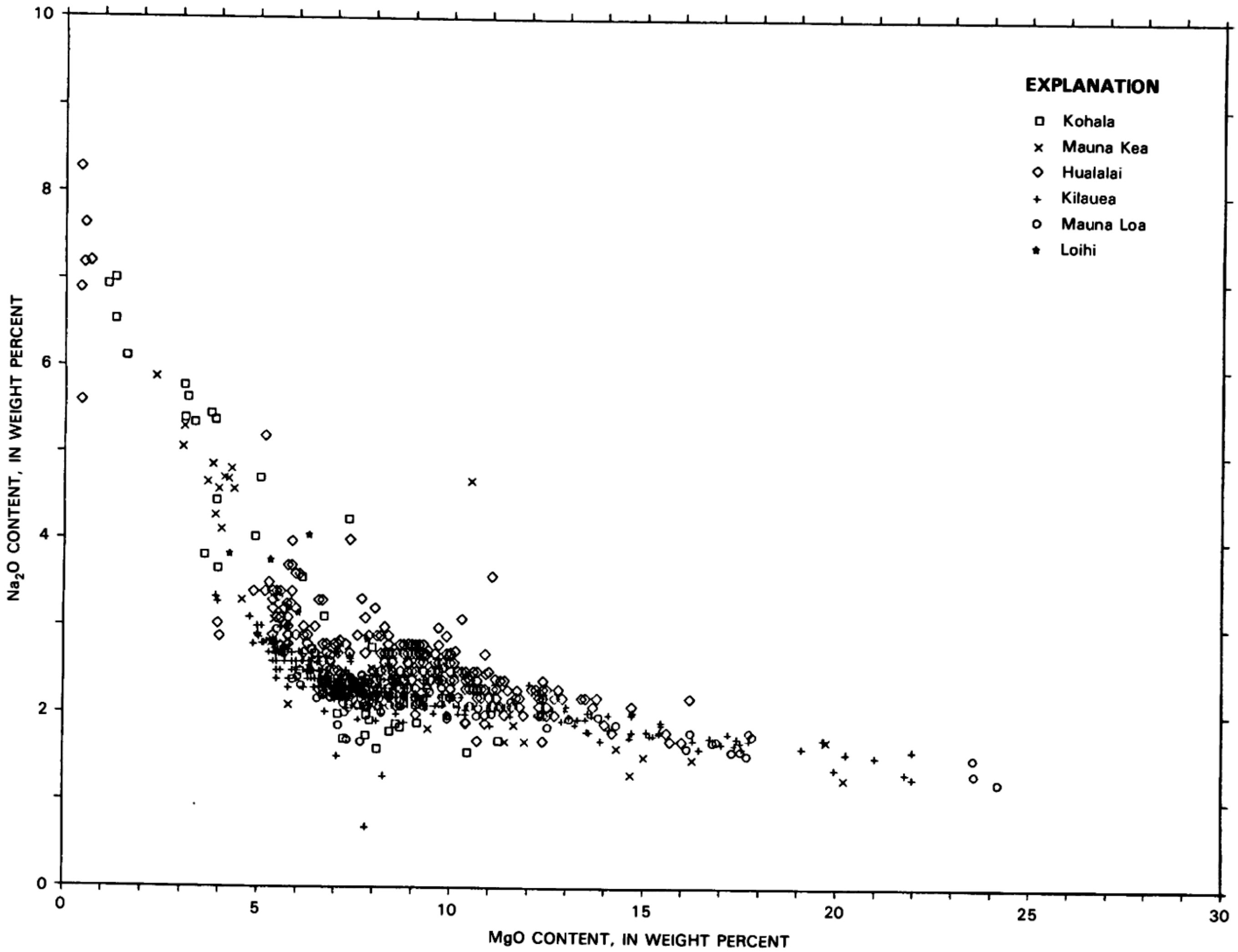

FIGURE 7.14.—Soda-magnesia variation diagram (Na_2O vs. MgO) for volcanic rocks of Hawaii. Analyses from published and unpublished sources.

TiO_2 contents; the two are distinct from the rocks of the other volcanoes. On figure 7.14 Mauna Kea rocks are seen to be similar to those of the other alkalic suites.

HUALALAI

Hualalai consists of a cap of alkalic lavas crowning an older tholeiitic shield (Moore and others, chapter 20). Exposed subaerial lavas are all alkalic; tholeiite has been recovered only from the submarine portion of the prominent northwest rift zone and (Clague, 1982) the bottoms of a few water wells. The geology of Hualalai was mapped in reconnaissance by Stearns and Macdonald (1946); detailed maps have been completed recently by D.A. Clague and by R.B. Moore.

About 5 km east of Hualalai's summit, a diffuse rift zone trends north from the principal northwest rift zone, which bends here and continues 13 km south-southeast. The subaerial portion of the northwest rift zone, 2–4 km wide, is 24 km long from the junction east of the summit to the ocean; bathymetry suggests that its submarine extension may be 70 km long. The north rift zone, about 10 km long and 5 km wide, contains less than 5 percent of the vents and has been inactive during the past 2,000 years. No ancient or modern caldera is evident, but there is, as on Mauna Kea, a concentration of vents in the summit area.

Trachyte, the most SiO_2-rich rock on the Island of Hawaii, crops out on the north rift zone of Hualalai at the Puu Waawaa cone and Puu Anahulu flow. Trachyte and microsyenite occur as xenoliths in basaltic deposits from four vents on the northwest and south-

TABLE 7.6.—*Selected references on the petrology and geochemistry of individual volcanoes of Hawaii*

Volcano	References
Kohala	Stearns and Macdonald (1946), Macdonald and Katsura (1964), Macdonald (1968), Feigenson and others (1983).
Mauna Kea	Stearns and Macdonald (1946), Macdonald and Katsura (1964), Macdonald (1968).
Hualalai	Moore and others (chapter 20), Stearns and Macdonald (1946), Macdonald (1968), Clague and others (1980).
Mauna Loa	Stearns and Macdonald (1946), Macdonald and Katsura (1964), Macdonald (1968), Wright (1971), Rhodes (1983).
Kilauea	Stearns and Macdonald (1946), Macdonald and Katsura (1964), Macdonald (1968), Wright (1971), Wright and Fiske (1971), Wright and others (1975), Wright and Tilling (1980), Wright 1984).
Loihi	Moore and others (1982), Frey and Clague (1983), Lanphere (1983).

southeast rift zones, and trachyte just above sea level was encountered in a drillhole on the northwest rift. A rather uncertain age for Puu Waawaa of 0.4 ± 0.3 Ma was obtained by Funkhouser and others (1968), but subsequently G.B. Dalrymple (written commun., 1985) determined an age of $0.106 \pm .006$ Ma. The steep topographic gradients in the area of the northwest rift zone suggest that other trachyte bodies may underlie a thin draping of more mafic lavas. Trachytes were produced during the Pleistocene, when magmatic activity was apparently much greater than it has been during the Holocene and much larger volumes of parental alkali olivine basalt were available for fractionation in shallow magma chambers.

Stearns and Macdonald (1946) mapped the alkalic rocks of Hualalai as the Hualalai Volcanic Series, which included the Waawaa Volcanics. These units are now called the Hualalai Volcanics and the Waawaa Trachyte Member, respectively (fig. 7.4; Langenheim and Clague, chapter 1, part II). Subsequent mapping and radiocarbon dating (Moore and others, chapter 20) have shown that about 95 percent of the surface is younger than 10 ka, and about 20 percent is younger than 1 ka. About 200 vents have erupted during Holocene time; the latest eruptions occurred in 1800–1801 (Stearns and Macdonald, 1946).

Hawaiite is the other differentiated lava that has been erupted by Hualalai; neither mugearite nor benmoreite, common on Kohala, has been found. The more silicic lavas are relatively old; during the last 5,000 years, most eruptions have produced olivine-controlled and differentiated alkali olivine basalt. Xenoliths include mafic and ultramafic rocks and are common in more than two dozen vents and associated flows. They are generally either rocks cognate to the volcano or fragments of oceanic crustal layer 3 (Jackson and others, 1981).

The alkali-silica variation diagram for Hualalai rocks (fig. 7.10*C*) shows that differentiation of alkalic magmas has produced the most silica-rich rocks on the island. It is possible that mugearites and benmoreites were formed during the period of trachyte volcanism, but they have never been found as flows, cones, or xenoliths.

Figure 7.11*C* shows the typical alkalic trend of decreasing CaO with increasing SiO_2, but it includes wide scatter at the basaltic end and a huge Daly gap (no lavas of intermediate silica content).

Figure 7.12*C* shows a wide scatter of CaO contents in the MgO range 5–15 percent, indicating that mixing of magmas has been an important process within Hualalai and reflecting the fact that phenocrysts of clinopyroxene and plagioclase locally are common. Figure 7.14 shows the higher soda content in alkalic rocks (analyses dominantly from Hualalai) vs. tholeiites.

MAUNA LOA

If the structurally high lavas in the Ninole Hills are considered to be part of Mauna Loa (Lipman, 1980), this volcano has been erupting above sea level for at least 400,000 years. Most of its surface, however, is Holocene, as mapped by Stearns and Macdonald (1946), Lipman and Swenson (1984), and Lockwood and others (1984, and unpublished data). Stearns and Macdonald (1946) divided Mauna Loa rocks into (1) the Pliocene Ninole Volcanic Series, shown by subsequent K-Ar dating (Evernden and others, 1964; Dalrymple, 1971) to be late Pleistocene; (2) the Pleistocene Kahuku Volcanic Series; and (3) the latest Pleistocene and Holocene Kau Volcanic Series. These units are now called the Ninole Basalt, the Kahuku Basalt, and the Kau Basalt (see fig. 7.4; Langenheim and Clague, chapter 1, part II). The Kahuku and Kau are separated by the Pahala Ash.

All known subaerial lavas of Mauna Loa are tholeiites, and most lavas are olivine controlled. Differentiated lavas are rare, in contrast to Kilauea (Wright, 1971). Figure 7.10*D* shows that a few of the more differentiated lavas plot close to the line separating alkalic from tholeiitic basalts (Macdonald and Katsura, 1964).

Figure 7.11*D* shows that CaO generally increases with increasing SiO_2 in Mauna Loa rocks, but begins to decrease as andesitic (52 percent SiO_2) compositions are approached. This trend reflects the removal of olivine (low in silica and lime) from tholeiitic melts. As andesitic compositions are approached, CaO begins to decrease, reflecting coprecipitation of pyroxene and (or) plagioclase, as in the alkalic trend.

Figure 7.12*D* (CaO vs. MgO) shows that most Mauna Loa tholeiites are olivine-controlled, as noted by Wright (1971) and Rhodes (1983). In a few cases, differentiated magmas (<6.8 percent MgO; Wright, 1971) have been mixed with olivine-controlled magmas to produce hybrid lavas whose compositions plot off the olivine-control line.

Figure 7.13*D* (TiO_2 vs. MgO) suggests that there are two trends among the Mauna Loa rocks. One has relatively low TiO_2 at specific MgO abundances and may reflect accumulation of ilmenite and (or) titanomagnetite.

KILAUEA

The oldest subaerial rocks of Kilauea were mapped as the Hilina Volcanic Series by Stearns and Macdonald (1946). The rocks in their lowermost exposures are thought to date from 100–70 ka (Easton and Garcia, 1980). Holcomb (1980) has determined that 90 percent of the surface of Kilauea is younger than 1.1 ka, and 70 percent is younger than 0.5 ka. The youngest rocks of Kilauea were mapped as the Puna Volcanic Series by Stearns and Macdonald (1946). The Puna is of latest Pleistocene and Holocene age. These units have been renamed the Hilina Basalt and the Puna Basalt by Easton (chapter 11). The Hilina and the Puna are separated by the Pahala Ash (see fig. 7.4).

The known eruptive vents of Kilauea are confined to its summit caldera (3 km by 5 km in size) and two rift zones that extend east and southwest from the summit. The east rift zone, which initially trends southeast for 6 km from the summit and then turns east-northeastward and extends another 45 km, is the longer and historically more frequently active of the two (Duffield and others, 1982). It extends below sea level another 70 km beyond the eastern end of the island (Moore and Reed, 1963; Fornari and others, 1978). The subaerial part of the southwest rift zone is about 32 km long, and no extension has been identified offshore.

The south flank of Kilauea is unbuttressed, in contrast to its north side, and thus it is free to move southward in response to repeated injection of magma into storage chambers beneath the summit and rift zones (Swanson and others, 1976a). The large earthquakes of 1868 and 1975 were possibly related to accumulated stress caused by rift deformation. The normal fault scarps of the Hilina system record cumulative displacements of at least 300 m.

Eruptions of Kilauea and Mauna Loa are normally placid and nonexplosive, but Mauna Loa has had minor phreatic eruptions in Holocene time and Kilauea experienced violent explosive eruptions in 1790 and 1924 and doubtless many times previously (Swanson and Christiansen, 1973; Decker and Christiansen, 1984). The 1790 event was probably phreatomagmatic and may have been associated with a major collapse that formed the modern caldera (Holcomb, 1980). Lavas of that age cover much of the lower east rift zone (Moore, 1981, 1983); draining of the summit magma reservoir to feed the eruptions on the rift zone likely induced the collapse. The 1924 phreatic eruption was preceded by the injection of magma from the summit reservoir into the east rift zone, accompanied by ground subsidence at Kapoho, near the subaerial terminus of the rift; a submarine eruption may have occurred to the east-northeast. The event climaxed with a series of steam explosions at Halemaumau over the course of several days. The combination of lava withdrawal, explosions, and collapse of the walls greatly increased both the diameter and depth of Halemaumau Crater.

Other large explosive eruptions on Kilauea built the Kapoho cone, only 20 m above sea level, a few hundred years ago, and were associated with collapse of the three largest pit craters on the lower east rift zone in the time interval 1.3 to 0.2 ka (Moore, 1981, 1983).

Many historical eruptions of Kilauea have lasted only a few days to a few weeks, but three relatively long-lived eruptions have built satellitic shields and associated cones (Mauna Iki, Mauna Ulu, and Puu Oo) since 1919. Two late prehistoric satellitic shields (Kane Nui o Hamo and Heiheiahulu) lie along the east rift zone; similar shields probably formed throughout the growth of the volcano and now the older ones lie buried. Long-lived eruptions from central vents along rift zones apparently were less common during most of the last 1,500 years than they have been during historical (post-1820) time.

All known Kilauea lavas are only tholeiitic basalt; olivine-controlled, differentiated, and hybrid lavas have been erupted from its rift zones, while summit lavas are all olivine-controlled (Wright and Fiske, 1971). As with a few Mauna Loa lavas, a few Kilauea lavas fall in the transition zone between tholeiitic and alkalic Hawaiian rocks on the alkali-silica variation diagram (fig. 7.10*E*). It can also be seen from figure 7.10*E* that, despite its relative youth, Kilauea has erupted a few lavas that are somewhat more differentiated than any that have been found on Mauna Loa. It is not known why the rift zones of Kilauea are able to accommodate long-lived magma chambers whereas those of Mauna Loa do not, but the reason may be related to the different heights of the two volcanoes.

The variation diagram of CaO vs. SiO_2 shows that Kilauea tholeiites are similar to those from Mauna Loa. CaO increases with increasing SiO_2 until andesitic compositions are approached and then decreases with further increase of SiO_2. The lime content of Kilauea tholeiitic differentiates is markedly higher than that in alkalic differentiates of the other volcanoes.

Plots of the variation of CaO and TiO_2 with MgO (figs. 7.12*E*, 7.13*E*) show olivine-controlled differentiation down to MgO abundances of about 6.8 percent; departures from the straight trend reflect magma mixing in rift-zone storage chambers (Wright and Fiske, 1971). Melts erupted on the rift zones range as low as 4.1 percent MgO and include both differentiated and hybrid lavas (Wright and Fiske, 1971). TiO_2 is generally higher in MgO-rich Kilauea lavas than in those from Hualalai and Mauna Loa.

LOIHI

Because of its early stage of development, Loihi Seamount was expected to consist exclusively of tholeiitic rocks, but dredged samples included alkali olivine basalts and basanites, some with abundant ultramafic xenoliths, as well as tholeiites (Moore and others, 1982). From this it has been concluded that limited partial melting of mantle source material during the initial stages of formation of Hawaiian volcanoes may result in generation of alkalic basalts (Moore and others, 1982; Frey and Clague, 1983). With increased partial melting, tholeiitic melts would form, and Loihi appears to be in a transitional stage between the generation of these two types of basalt.

It is also possible, however, that the rocks of Loihi represent more than one mantle source. Lanphere (1983) reported $^{87}Sr/^{86}Sr$ ratios for the different groups of basalts recovered from Loihi and concluded that their mantle sources had different Sr-isotope compositions.

Analytical data reported by Moore and others (1982) are incorporated here in figures 7.10–7.14. The variation diagram of Na_20+K_20 vs. SiO_2 (fig. 7.10*F*) shows that Loihi alkalic and tholeiitic basalts are similar to those from other volcanoes on the Island of Hawaii, but no other basanites have been reported.

The field of high-CaO Loihi rocks is evident on figures 7.11*F* and 7.12*F*. Figures 7.13*F* and 7.14 further indicate that analyzed Loihi rocks are generally similar to those from other Hawaiian volcanoes and that olivine-controlled differentiation and mixing of magmas have occurred.

NONERUPTIVE GEOLOGIC PROCESSES

Hawaii is the youngest island of the archipelago and the only one with appreciable historical volcanic activity, and any review of its geologic history necessarily deals chiefly with the growth and construction processes related to volcanism. However, geologic agents other than volcanism have also been at work, some constantly and others sporadically. During the active growth stages of a volcano their effects are commonly outstripped or covered by the effects of volcanism, but during the later evolutionary stages, when the frequency and volume rate of eruptions decline, the effects of these other geologic agents become more apparent.

EROSION AND SEDIMENTATION

Extensive discussions of the effects of erosion and sedimentation on the Island of Hawaii are given elsewhere, chiefly in Stearns and Macdonald (1946) and Macdonald and others (1983); we present only a brief summary here.

Annual rainfall on the windward side of Hawaii (east and northeast) is high, as much as 7,600 mm (300 inches). Erosion has been effective in cutting canyons on the windward slopes of the older volcanoes, Kohala and Mauna Kea, and to some extent in the old Ninole Hills on the south flank of Mauna Loa. In these areas of steep topography, soil creep and mudflows locally contribute to the process of erosion. The leeward (west and southwest) side of the island receives much less rainfall, locally as little as 250 mm (10 inches). As a consequence, the western flanks of Kohala and Mauna Kea are little dissected by streams. Hualalai, Kilauea, and most of Mauna Loa show little evidence of stream erosion, because the surface has been frequently renewed by Holocene volcanic activity. Another important factor inhibiting stream erosion is the porous nature of young volcanic rocks. Even heavy rain infiltrates young lava flows quickly, and surface runoff is minimal.

As noted by Stearns and Macdonald (1946), Macdonald and others (1983), and other workers, the locations of canyons on the northeastern side of Kohala are partly fault-controlled and partly consequent, initially cut near the edges of lava flows. Their local relief is as much as 500 m. Submergence of the island during latest Pleistocene and Holocene time has drowned the valley mouths, and the major canyons, including Waipio, Waimanu, Honokane Nui, and Pololu, contain thick sedimentary fill.

Canyons cut into the windward flank of Mauna Kea are not as deep (maximum 200 m) as those on Kohala, because the surface of Mauna Kea is younger. Radial drainage consequent upon the lava-flow topography dominates; slopes are thinly mantled by locally derived cinders, and the effect of structures, such as buried faults, appears to be minimal. The Wailuku River, which flows through part of Hilo, is primarily a consequent stream cut near the edges of Mauna Loa flows that lapped onto the flank of Mauna Kea.

The Ninole Hills, on the south flank of Mauna Loa, are either structurally high (Lipman, 1980) or erosional (Stearns and Macdonald, 1946) remnants of early Mauna Loa. Gulches that separate the hills are likely inherited from Pleistocene time; their positions can still be identified even though they have been buried by flows of the younger Kahuku and Kau Basalts.

Marine erosion has been vigorous, primarily on the windward sides of the island, and has formed sea cliffs as high as 400 m on Kohala and 100 m on Mauna Kea (Macdonald and others, 1983). Sea stacks and caves are common on the Hamakua coast. Wave action along the southeastern coast has formed sea cliffs several meters high on historic and prehistoric flows from vents on Kilauea's east rift zone. Erosion along this coast is so vigorous that a wave-cut face 1–3 m high was maintained even while lava from the east rift zone of Kilauea was still actively flowing into the sea (Peterson, 1976); within months of the cessation of activity, the newly created shoreline had been worn back appreciably. In contrast, marine erosion of flows from Kohala, Mauna Kea, Hualalai, and Mauna Loa on the western (leeward) side of the island has been slight, and sea cliffs higher than a few meters are rare, even on the older (Pleistocene) flows.

Eolian erosion and sedimentation have been of local importance on the island. Extensive areas on the west flank of Mauna Kea are covered by eolian silt, which originated chiefly as ash at vents and perhaps as glacial debris blown from the summit area. Dunes consisting of reworked Pahala ash are common in the South Point area on the southern flank of Mauna Loa. The Kau Desert, on the southwest flank of Kilauea, has many small active dunes that consist primarily of wind-blown pyroclastic debris originally ejected during the explosive eruptions of 1790 and 1924.

CHANGES OF SEA LEVEL

Many workers have studied changes of sea level in the Hawaiian Islands, especially H.T. Stearns and more recently J.G. Moore. The major controls on sea level have been (1) worldwide eustatic fluctuations caused by Quaternary climatic changes resulting in varying amounts of water stored in glaciers and (2) subsidence of the islands as a result of volcanic load (Moore, chapter 2, 1969).

Ancient shorelines have been identified throughout the Hawaiian Islands by wavecut terraces below and near sea level and by deposits above sea level inferred to represent marine terraces (Stearns, 1946, 1966, 1978; Macdonald and others, 1983). These widely separated stands of the sea suggested to Stearns that the crust has repeatedly oscillated up and down throughout Quaternary time. In view of the ongoing subsidence of the southeastern end of the island chain, readily shown to be caused by the persistent process of volcanic loading (Moore, chapter 2; Apple and Macdonald, 1966; Moore, 1970; Moore and Fornari, 1984), such large-amplitude fluctuations were puzzling. Moore and Moore (1984), however, have provided evidence showing that most or all of the supposed subaerial terrace deposits have instead resulted from a giant catastrophic wave, which avoids the need to explain high stands of sea level by crustal oscillation. Moore (chapter 2) discusses the subsidence processes in detail.

If, however, another major global glaciation occurs, sea level may drop faster than the ongoing subsidence. Canyon-cutting on the

Island of Hawaii would then become more vigorous, as streams become graded to the new lower sea level.

GLACIATION

Mauna Kea was glaciated during Pleistocene time, and the resulting deposits were studied by Wentworth and Powers (1941), Porter and others (1977), and Porter (1979a, b). These workers recognized the effects of four separate glaciations that occurred during the period 280–10 ka. Typical glacial features such as striated boulders, roches moutonnees, ground moraine, and lateral and terminal moraines are visible in the summit area of Mauna Kea. Porter (1979b) estimated that the maximum thickness of ice was 150–170 m.

Glaciers may have formed on Mauna Loa also, but any evidence of them has been buried by Holocene lavas (Macdonald and others, 1983).

EARTHQUAKES AND FLANK DISPLACEMENTS

Most earthquakes on and near the Island of Hawaii are the consequence of volcanic activity. Some are induced as magma moves into storage chambers beneath the summits of Mauna Loa and Kilauea, others as magma is intruded into the rift zones that radiate from the summit calderas. The intrusion of magma results in an accumulation of stress that must eventually be relieved. Some earthquakes occur when magma moves out of an area, resulting in local foundering of overlying rocks.

Large earthquakes (magnitude 6 or greater) in Hawaii have been concentrated in three principal areas: (1) the Kealakekua fault system on the west flank of Mauna Loa, (2) the Kaoiki fault system on the southeast flank of Mauna Loa, and (3) the Hilina fault system on the south flank of Kilauea. Each of these areas has experienced at least one earthquake of magnitude (M) greater than 6 since 1950. In addition, a deep (48-km) $M=6.2$ earthquake struck the east flank of Mauna Kea in 1973 and apparently triggered sympathetic crustal aftershocks on the north flank of Mauna Kea, an area that has experienced occasional swarms for decades (Unger and Ward, 1979).

Earthquakes that occur on the Kealakekua and Hilina fault systems are, in large part, the result of gravitational sliding of parts of the volcanic edifices toward the sea. In these areas, there is no adjoining volcano to provide a buttress against such sliding; thus, when the volcano is overinflated (as Mauna Loa was in the aftermath of the great 1950 eruption and as the east rift zone of Kilauea was by the end of the 1969–1974 Mauna Ulu eruption), a condition of accumulated strain analogous to oversteepening results in failure of the volcano's flank (Swanson and others, 1976a).

Large earthquakes in the Kaoiki region probably are largely the result of inflation of the summit region and upper northeast rift zone of Mauna Loa. Here the strain release is accommodated by strike-slip faulting (Endo, 1985) rather than by normal faulting, because the presence of Kilauea provides a buttress resisting downward slippage of Mauna Loa's southeast flank.

Large fault scarps, as high as about 300 m, are the major surface expression of repeated faulting along the Hilina and Kealakekua systems. The Kaoiki system consists of upper and lower parts. The lower part is inactive seismically, and fault scarps there have been buried by lava flows as old as 9 ka (Lipman, 1980). The upper part, where modern seismicity is concentrated, is characterized by extensive ground cracking, but fault scarps of large displacement are absent (Endo, 1985).

TSUNAMIS

Tsunamis (seismic-induced sea waves) are the most dangerous and destructive natural hazards that affect Hawaii and its residents. Hawaiian tsunamis usually are caused by earthquakes of local or circum-Pacific origin that displace the ocean bottom; this displacement in turn generates a wave in the overlying water. These low-amplitude waves travel at speeds of several hundred kilometers per hour in deep ocean, but when they approach land masses they are slowed and build up to heights of many meters. The greatest recorded height of a wave striking the Island of Hawaii was 16.8 m at the mouth of Pololu Valley in 1946, although greater (but unmeasured) heights may have been reached in 1868 and at other times (Macdonald and others, 1983).

Tsunamis that have struck Hawaii since 1819 are listed in table 7.7. The average interval between tsunamis has been about five years, but the average interval separating the seven that have caused severe damage has been about 22 years. However, their recurrence interval has no regular pattern.

TABLE 7.7.—*Principal tsunamis observed in Hawaii during historical time*
[Adapted from Macdonald and others, 1947, 1983]

Date	Source	Damage in Hawaii
1819, April 12	Unknown	Unknown
1837, November 7	South America	SEVERE
1841, May 17	Kamchatka	Slight
1868, April 2	Hawaii	SEVERE
1868, August 13	South America	SEVERE
1869, July 25	South America (?)	Moderate
1872, August 23	Hawaii	Slight
1877, May 10	South America	SEVERE
1883, August 26	East Indies	Slight
1896, June 15	Japan	None
1901, August 9	Japan (?)	None
1906, January 31	Unknown	None
1906, August 16	South America	Slight
1918, September 7	Kamchatka	Slight
1919, April 30	Unknown	None
1922, November 11	South America	None
1923, February 3	Kamchatka	Moderate
1923, April 13	Kamchatka	None
1927, November 4	California	None
1927, December 28	Kamchatka	None
1928, June 16	Mexico	None
1929, March 6	Aleutian Islands	None
1931, October 3	Solomon Islands	None
1933, March 2	Japan	Slight
1938, November 10	Alaska	None
1944, December 7	Japan	None
1946, April 1	Aleutian Islands	SEVERE
1952, November 4	Kamchatka	Slight
1957, March 9	Aleutian Islands	Slight
1960, May 22	South America	SEVERE
1964, March 28	Alaska	None
1975, November 29	Hawaii	SEVERE

The effects of tsunamis are not likely to be preserved in the geologic record for very long. Vegetation generally grows rapidly in Hawaii and would mask debris. Boulders are thrown up on the tops of low sea cliffs also by severe storms, and these would be indistinguishable from those washed up by tsunamis. Deep narrow canyons (Pololu, Laupahoehoe) on the northeastern coast, which are most vulnerable to severe tsunami damage, are rapidly filled with new fluvial sediments. On the other hand, Moore and Moore (1984) interpreted a widespread gravel on Lanai, Maui, and northwest Hawaii as a deposit from a giant wave, possibly generated by a submarine landslide south of Lanai dating from about 100 ka. This event, however, was much larger and rarer than ordinary tsunamis.

FUTURE DEVELOPMENT

KOHALA

Kohala Volcano is generally considered extinct, because its last known eruption occurred at about 60 ka (McDougall and Swanson, 1972). However, renewed volcanism on other Hawaiian volcanoes has begun one million or more years after cessation of alkalic cap activity (Clague and Dalrymple, chapter 1, part I). Future eruptions of Kohala thus are possible; they might be alkalic basaltic, basanitic, or nephelinitic in composition.

Erosion is probably the major geologic process that will affect Kohala in the future. Unless parts are rebuilt by renewed volcanic activity, sustained fluvial and coastal erosion for millions of years will wear Kohala down to sea level. If regional subsidence continues in the future as it has in the past (Moore, chapter 2), subsidence will supplement the erosion process. Kohala will become a separate island long before it is leveled by erosion, if subsidence causes the saddle between it and Mauna Kea to be submerged.

MAUNA KEA

Mauna Kea may well erupt again, since it has been only about 4,500 years since it last erupted (Porter and others, 1977). The next eruptions may be similar in composition to the most recent (hawaiite), although it is possible that mugearite, benmoreite, or trachyte will appear in the future. Mauna Kea is still considered to be in the capping stage (3) although unless additional eruptions of alkalic rocks occur, it will have quietly completed the transition to the erosional stage (4).

As on Kohala, erosion will be the major geologic process occurring on Mauna Kea. Over the next few millions of years, erosion and subsidence probably will reduce the volcano to sea level.

HUALALAI

The average recurrence interval for eruptions of Hualalai in the Holocene has been about 50 yr (200 events in 10,000 yr), but clusters of eruptions separated by gaps of hundreds of years have apparently occurred. A few satellitic shields that probably took several years to form are present. Most of the recent eruptions have been of high volume (>0.25 km^3). Phreatic explosions have occurred at two vents within the past 700 years; the products of one covered an area of at least 10 km^2. Eruptions since at least 100 ka have been exclusively of alkali olivine basalt and its differentiates; no major change in chemical composition is expected for tens of thousands of years. Perhaps in hundreds of thousands of years Hualalai will erupt basanite and (or) nephelinite. An intense swarm of earthquakes beneath Hualalai in 1929 is believed to have been associated with underground movement of magma (Macdonald and Abbott, 1970, p. 53–54), and the volcano may have been close to having an eruption (Moore and others, chapter 20). Since 1929, however, neither ground deformation nor swarms of earthquakes have been detected on Hualalai, so it cannot be estimated when the next magmatic activity will occur.

Hualalai is virtually undissected, although a few intermittent streams are subject to flash flooding. Heavy rain in 1980 and 1981 resulted in deposition of several hundred cubic meters of debris in alluvial fans near the summit and downcutting of gullies by as much as 5 m. On the southwest flank of the volcano, gullying locally occurs on flows that are relatively old (13–5 ka). The surface renewal rate (18 km^2 per 100 yr for the last 3,000 yr) suggests that erosion will not have a pronounced effect on Hualalai's morphology for a long time, possibly tens of thousands of years.

MAUNA LOA

Mauna Loa has been active about 6 percent of the time since 1835, and a similar rate of activity likely will continue in the foreseeable future. Mauna Loa has erupted an average of 2.9 km^3 of lava per century during historical time, and most of its surface is younger than 4 ka (Lockwood and Lipman, chapter 18). Historical Mauna Loa eruptions have ranged in duration from a few hours to 450 days, and future eruptions from the summit, rift zones, and north and west flanks probably will be similar. Mauna Loa does not seem to build satellitic shields, in contrast to Kilauea. In view of the prevailing rate of crustal subsidence (Moore, chapter 2), it seems unlikely that the height of Mauna Loa above sea level will increase much more than a few tens or hundreds of meters; however, repeated filling and collapse of Mokuaweoweo Crater seems likely to occur.

If Mauna Loa follows the pattern of most other Hawaiian volcanoes, thousands to hundreds of thousands of years in the future, it will erupt alkalic basalts and their differentiates. As noted earlier, a few basalts of Mauna Loa already appear to be transitional in their chemical composition.

Mauna Loa is nearly undissected; until the output of the volcano decreases markedly, erosion will have negligible effect on its constructional landforms.

KILAUEA

Kilauea has been active about 60 percent of historical time and has extruded more than 1.2 km^3 of tholeiitic basalt since 1952. Three satellitic shields have formed during this century, and two others during the past few hundred years. In contrast to Mauna Loa, Kilauea has sustained long-term eruptions (at least 5 years). Magma will continue to be stored in its rift zones, where it will differentiate; perhaps more differentiates as extreme as the Yellow

Cone scoria will form and be erupted. Eventually, basalts more transitional in composition will be erupted, although Kilauea seems unlikely to erupt alkalic rocks until its present rate of magma production declines. That may be hundreds of thousands of years in the future.

Kilauea also is little eroded, although a few intermittent streams flood during heavy rains. Kilauea's historical output of about 2.2 km^3/100 yr seems likely to ensure that its surface will be frequently renewed; at present, 90 percent of its surface is younger than 1.1 ka (Holcomb, chapter 12).

LOIHI

If Loihi erupts in the future at a rate comparable to those of Kilauea and Mauna Loa, its summit will reach the ocean's surface in a few tens of thousands of years. Moore and others (1982) suggested that Loihi has been or may soon begin erupting tholeiitic basalt exclusively as the amount of partial melting of the mantle source increases. If it reaches sea level, it will initially form a separate island, but if eruptions continue, it could ultimately be joined with Hawaii. Loihi likely will follow the same eruptive pattern as other volcanoes along the island chain.

REFERENCES CITED

Ando, M., 1979, The Hawaii earthquake of November 29, 1975: low dip angle faulting due to forceful injection of magma: Journal of Geophysical Research, v. 84, no. B 13, p. 7616–7626.

Apple, R.A., and Macdonald, G.A., 1966, The rise of sea level in contemporary times at Honaunau, Kona, Hawaii: Pacific Science, v. 20, p. 125–136.

Banks, N.G., Klein, F.W., Moore, R.B., Jackson, D.B., and Okamura, A.T., 1981, Kilauea Volcano November 1979 eruption [abs]: Eos (American Geophysical Union Transactions), v. 62, no. 45, p. 1072.

Banks, N.G., Wolfe, E.W., Duggan, T.A., Okamura, A.T., Koyanagi, R.Y., Greenland, L.P., and Jackson, D.B., 1983, Magmatic events at Kilauea Volcano, Hawaii, 1982 [abs.]: Eos (American Geophysical Union Transactions), v. 64, no. 45, p. 901–902.

Bargar, K.E., and Jackson, E.D., 1974, Calculated volumes of individual shield volcanoes along the Hawaiian-Emperor Chain: U.S. Geological Survey Journal of Research, v. 2, p. 545–550.

Beaglehole, J.C., 1967, The journals of Captain Cook on his voyages of discovery; Volume III: The voyage of the Resolution and Discovery, 1776–1780: Cambridge University Press, 1647 p.

Berry, A.L., 1973, Thermoluminescence of Hawaiian basalts: Journal of Geophysical Research, v. 78, p. 6863–6867.

Brigham, W.T., 1909, The volcanoes of Kilauea and Mauna Loa: B.P. Bishop Museum Memoir, v. 2, no. 4, 222 p.

Budahn, J.R., and Schmitt, R.A., 1985, Petrogenetic modeling of Hawaiian tholeiitic basalts: a geochemical approach: Geochimica et Cosmochimica Acta, v. 49, p. 67–87.

Clague, D.A., 1982, Petrology of tholeiitic basalt dredged from Hualalai Volcano, Hawaii: Eos (American Geophysical Union Transactions), v. 63, p. 1138.

———in press, Hawaiian alkaline volcanism: Quarterly Journal, Geological Society of London.

Clague, D.A., Jackson, E.D., and Wright, T.L., 1980, Petrology of Hualalai Volcano, Hawaii: implication for mantle composition: Bulletin Volcanologique, v. 43, no. 4, p. 641–656.

Coan, T., 1841, Great eruption of the volcano of Kilauea: Missionary Herald, v. 37, p. 283–285.

———1851, Mauna Loa eruption of 1849: American Journal of Science, 2d ser., v. 12, p. 82.

———1852, On the eruption of Mauna Loa, Hawaii, February 1852: American Journal of Science, 2nd ser., v. 14, p. 106–107, 219–224.

———1869, Notes on the recent volcanic disturbances of Hawaii: American Journal of Science, 2nd ser., v. 47, p. 89–98.

———1871, On Kilauea and Mauna Loa: American Journal of Science, 3d ser., v. 2, p. 454–456.

———1877, Volcanic eruptions on Hawaii: American Journal of Science, 3d ser., v. 14, p. 68–69.

Cross, Whitman, 1915, Lavas of Hawaii and their relations: U.S. Geological Survey Professional Paper 88, 97 p.

Crosson, R.S., and Endo, E.T., 1981, Focal mechanisms of earthquakes related to the 29 November 1975 Kalapana, Hawaii, earthquake: the effect of structure models: Bulletin of the Seismological Society of America, v. 71, no. 3, p. 713–729.

———1982, Focal mechansims and locations of earthquakes in the vicinity of the 1975 Kalapana earthquake aftershock zone 1970–1979: implications for tectonics of the south flank of Kilauea Volcano, Island of Hawaii: Tectonics, v. 1, p. 495–542.

Dalrymple, G.B., 1971, Potassium-argon ages from the Pololu Volcanic Series, Kohala Volcano, Hawaii: Geological Society of America Bulletin, v. 82, p. 1997–1999.

Dalrymple, G.B., Silver, E.A., and Jackson, E.D., 1973, Origin of the Hawaiian Islands: American Scientist, v. 61, p. 294–308.

Daly, R.A., 1911, The nature of volcanic action: American Academy of Arts and Sciences, Proceedings, v. 47, p. 47–122.

———1914, Igneous rocks and their origin: New York, McGraw-Hill Book Co., 563 p.

———1933, Igneous rocks and the depths of the earth: New York, McGraw-Hill Book Co., Inc., 598 p.

———1944, Volcanism and petrogenesis as illustrated in the Hawaiian Islands: Geological Society of America Bulletin, v. 55, p. 1363–1400.

Dana, J.D., 1849, Geology: U.S. Exploring Expedition, under the command of Charles Wilkes, U.S.N., 1838–1842: v. 10, p. 156–226.

———1859, Eruption of Mauna Loa, Hawaii: American Journal of Science, 2d ser., v. 27, p. 410–415.

———1860, Eruption of Mauna Loa, Sandwich Islands: American Journal of Science, 2d ser., v. 29, p. 301–302.

———1890, Characteristics of Volcanoes: New York, Dodd, Mead Co., 399 p.

Davis, J.B., 1859, Great eruption of the volcano Mauna Loa, in the Island of Hawaii: Edinburgh New Philosophical Journal, new ser., v. 10, p. 94–97.

Decker, R.W., and Christiansen, R.L., 1984, Explosive eruptions of Kilauea Volcano, Hawaii: *in* Explosive volcanism: inception, evolution, and hazards: Washington, D.C., National Academy Press, p. 122–132.

Douglas, D., 1914, Journal kept by David Douglas during his travels in North America, 1833–1837, London, p. 298–317.

Duffield, W.A., 1975, Structure and origin of the Koae fault system, Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 856, 12 p.

Duffield, W.A., Christiansen, R.L., Koyanagi, R.Y., and Peterson, D.W., 1982, Storage, migration, and eruption of magma at Kilauea Volcano, Hawaii, 1971–1972: Journal of Volcanology and Geothermal Research, v. 13, p. 273–307.

Dutton, C.E., 1884, Hawaiian volcanoes: U.S. Geological Survey, 4th Annual Report, p. 75–219.

Dzurisin, Daniel, 1980, Influence of fortnightly earth tides at Kilauea Volcano, Hawaii: Geophysical Research Letters, v. 7, p. 925–928.

Easton, R.M., and Garcia, M.O., 1980, Petrology of the Hilina Formation, Kilauea Volcano, Hawaii: Bulletin Volcanologique, v. 43, p. 657–673.

Ellis, William, 1827, Journal of William Ellis, Narrative of a tour of Hawaii, with remarks on the history, traditions, manners, customs, and language of the inhabitants of the Sandwich Islands: Honolulu (1963), Advertiser Publishing Co., Ltd., reprint of the London 1827 edition, 342 p.

Endo, E.T., 1985, Seismotectonic framework for the southeast flank of Mauna Loa Volcano, Hawaii: Seattle, University of Washington, Ph.D. dissertation, 327 p.

Evernden, J.F., Savage, D.E., Curtis, G.H., and James, G.T., 1964, Potassium-argon dates and the Cenozoic mammalian chronology of North America:

American Journal of Science, v. 262, p. 145–198.

Feigenson, M.D., Hofmann, A.W., and Spera, F.J., 1983, Case studies on the origin of basalt, II. The transition from tholeiitic to alkalic volcanism on Kohala Volcano, Hawaii: Contributions to Mineralogy and Petrology, v. 84, p. 390–405.

Finch, R.H., and Macdonald, G.A., 1951, Report of the Hawaiian Volcano Observatory for 1948 and 1949: U.S. Geological Survey Bulletin 974–D, p. 103–133.

———1953, Hawaiian volcanoes during 1950: U.S. Geological Survey Bulletin 996–B, p. 27–89.

Fisher, R.V., 1968, Puu Hou littoral cones, Hawaii: Geologisches Rundschau, v. 57, p. 837–864.

Fiske, R.S., and Jackson, E.D., 1972, Orientation and growth of Hawaiian volcanic rifts: the effect of regional structure and gravitational stresses: Proceedings of the Royal Society of London, v. 329, p. 299–326.

Fiske, R.S., and Koyanagi, R.Y., 1968, The December 1965 eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 607, 21 p.

Fornari, D.J., Malahoff, A., and Heezen, B.C., 1978, Volcanic structure of the crest of the Puna Ridge, Hawaii: geophysical implications of submarine volcanic terrain: Geological Society of America Bulletin, v. 89, p. 605–616.

Frey, F.A., and Clague, D.A., 1983, Geochemistry of diverse basalt types from Loihi Seamount, Hawaii: petrogenetic implications: Earth and Planetary Science Letters, v. 66, p. 337–355.

Funkhouser, J.G., Barnes, I.L., and Naughton, J.J., 1968, The determination of a series of ages of Hawaiian volcanoes by the potassium-argon method: Pacific Science, v. 22, p. 369–372.

Furumoto, A.S., and Kovach, R.L., 1979, The Kalapana earthquake of November 29, 1975: an intra-plate earthquake and its relations to geothermal processes: Physics of the Earth and Planetary Interiors, v. 29, p. 355–364.

Goodrich, Joseph, 1826, Notice of the volcanic character of the Island of Hawaii: American Journal of Science, lst series, v. 11, p. 2–7.

Green, W.L., 1887, Vestiges of the molten globe, Pt. 2 of the Earth's surface features and volcanic phenomena: Honolulu, 377 p.

Halbig, J.B., Orr, J.B., and Lockwood, J.P., 1979, Use of alteration rind thickness to date prehistoric Hawaiian lavas: Hawaii Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, Abstract Volume, p. 163.

Harvey, A.G., 1947, Douglas of the fir, A biography of David Douglas, Botanist: Cambridge, Mass., Harvard University Press, 290 p.

Hitchcock, C.H., 1909, Hawaii and its volcanoes: Honolulu, The Hawaiian Gazette Co., Ltd., 314 p. (2nd edition with supplement, 1911).

Holcomb, R.T., 1976, Complexity and hazards of Hawaiian shield volcanoes [abs]: Geological Society of America, Abstracts with Program, v. 8, no. 6, p. 920–921.

———1980, Kilauea Volcano, Hawaii: chronology and morphology of the surficial lava flows: Stanford University, Ph.D. dissertation, 321 p., also U.S. Geological Survey Open-File Report 81–354, 1981.

Jackson, D.B., Swanson, D.A., Koyanagi, R.Y., and Wright, T.L., 1975, The August and October 1968 east rift eruptions of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 890, 33 p.

Jackson, E.D., Beeson, M.H., and Clague, D.A., 1982, Xenoliths in volcanic rocks from Mauna Kea Volcano, Hawaii: U.S. Geological Survey Open-File Report 82–201, 19 p.

Jackson, E.D., Clague, D.A., Engleman, E., Friesen, W.B., and Norton, D., 1981, Xenoliths in the alkalic basalt flows from Hualalai Volcano, Hawaii: U.S. Geological Survey Open-File Report 81–1031, 32 p.

Jaggar, T.A., 1919, Activity of Mauna Loa: Hawaiian Volcano Observatory Bulletin, v. 7, no. 10, p. 128–158.

———1920, Seismometric investigation of the Hawaiian lava column: Seismological Society of America Bulletin, v. 10, p. 155–275.

———1926, Journal of Mauna Loa eruption: Hawaiian Volcano Observatory Bulletin, v. 14, p. 31–47, 54–57.

———1947, Origin and development of craters: Geological Society of America Memoir 21, 508 p.

Jaggar, T.A., and Finch, R.H., 1924, The explosive eruption of Kilauea in Hawaii, 1924: American Journal of Science, ser. 5, v. 8, p. 353–374.

Kelley, M.L., 1979, Radiocarbon dates from the Hawaiian Islands—a compilation: U.S. Geological Survey Open File Report 79–1700, 37 p.

Kelley, M.L., Spiker, E.C., Lipman, P.W., Lockwood, J.P., Holcomb, R.T., and Rubin, M., 1979, U.S. Geological Survey, Reston, Virginia, Radiocarbon dates XV: Mauna Loa and Kilauea Volcanoes, Hawaii: Radiocarbon, v. 21, p. 306–320.

Kinoshita, W.T., Koyanagi, R.Y., Wright, T.L., and Fiske, R.S., 1969, Kilauea Volcano; the 1967–1968 summit eruption: Science, v. 166, p. 459–468.

Klein, F.W., and Koyanagi, R.Y., 1979, Seismicity of Kilauea and Loihi Volcanoes, Hawaii: Hawaii Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, Abstract Volume, p. 124.

Kuno, H., Yamasake, K., Iida, C., and Nagashima, K., 1957, Differentiation of Hawaiian magmas: Japan Journal of Geology and Geography, v. 28, p. 179–218.

Lanphere, M.A., 1983, $^{87}Sr/^{86}Sr$ ratios for basalt from Loihi Seamount, Hawaii: Earth and Planetary Science Letters, v. 66, p. 380–387.

Lanphere, M.A., Dalrymple, G.B., and Clague, D.A., 1980, Rb-Sr systematics of basalts from the Hawaiian-Emporer volcanic chain: Initial Reports of the Deep Sea Drilling Project, 55, p. 695–706.

Ledyard, John, 1783, A journal of Captain Cook's last voyage to the Pacific Ocean and in quest of a northwest passage between Asia and America: Hartford, Conn., Nathaniel Patkon.

Leeman, W.P., Budahn, J.R., Gerlach, D.C., Smith, D.R., and Powell, B.N., 1980, Origin of Hawaiian tholeiites: Trace element constraints: American Journal of Science, v. 280-A, p. 794–819.

Lipman, P.W., 1980, The southwest rift zone of Mauna Loa: implications for structural evolution of Hawaiian volcanoes: American Journal of Science, v. 280-A, p. 752–776.

Lipman, P.W., and Swenson, Alan, 1984, Generalized geologic map of the southwest rift zone of Mauna Loa Volcano, Hawaii: U.S. Geological Survey Miscellaneous Investigations Series Map I– 1323, scale 1:100,000.

Lockwood, J.P., Banks, N.G., English, T.T., Greenland, L.P., Jackson, D.B., Johnson, D.J., Koyanagi, R.Y., McGee, K.A., Okamura, A.T., and Rhodes, J.M., 1985, The 1984 eruption of Mauna Loa Volcano, Hawaii: Eos, Transactions, American Geophysical Union, v. 66, no. 16, p. 169–171.

Lockwood, J.P., Koyanagi, R.Y., Tilling, R.I., Holcomb, R.T., and Peterson, D.W., 1976, Mauna Loa threatening: Geotimes, v. 21, no. 6, p. 12–15.

Lockwood, J.P., and Lipman, P.W., 1980, Recovery of datable charcoal beneath young lavas: lessons from Hawaii: Bulletin Volcanologique, v. 43, no. 3, p. 609–615.

Macdonald, G.A., 1947, Bibliography of the geology and water resources of the Island of Hawaii: Hawaii Division of Hydrography, Bulletin 10, 191 p.

———1949a, Petrography of the Island of Hawaii: U.S. Geological Survey Professional Paper 214–D, p. 51–95.

———1949b, Hawaiian Petrographic Province: Geological Society of America Bulletin, v. 60, p. 1541–1596.

———1954, Activity of Hawaiian volcanoes during the years 1940–1950: Bulletin Volcanologique, ser. 2, v. 15, p. 120–179.

———1955, Hawaiian Islands: Catalog of the active volcanoes of the world including solfatara fields, Part III, International Volcanological Association, Naples, Italy, 37 p.

———1959, The activity of Hawaiian volcanoes during the years 1951–1956: Bulletin Volcanologique, ser. 2, v. 22, p. 3–70.

———1960, Dissimilarity of continental and oceanic rock types: Journal of Petrology, v. 1, p. 172–177.

———1962, The 1959 and 1960 eruptions of Kilauea Volcano, Hawaii, and the construction of walls to restrict the spread of the lava flows: Bulletin Volcanologique, v. 24, p. 249–294.

———1965, Hawaiian calderas: Pacific Science, v. 19, p. 320–334.

———1968, Composition and origin of Hawaiian lavas: Geological Society of America Memoir 116, p. 477–522.

———1972, Volcanoes: Englewood Cliffs, N.J., Prentice-Hall, Inc., 510 p.

Macdonald, G.A., and Abbott, A.T., 1970, Volcanoes in the sea: Honolulu, University of Hawaii Press, 441 p.

Macdonald, G.A., Abbott, A.T., and Peterson, F.L., 1983, Volcanoes in the sea, second edition: Honolulu, University of Hawaii Press, 517 p.

Macdonald, G.A., and Eaton, J.P., 1957, Hawaiian volcanoes during 1954: U.S. Geological Survey Bulletin 1061–B, 17–72.

———1964, Hawaiian volcanoes during 1955: U.S. Geological Survey Bulletin 1171, 170 p.

Macdonald, G.A., and Katsura, T., 1961, Variations in the lava of the 1959 eruption in Kilauea Iki: Pacific Science, v. 15, p. 358–369.

———1962, Relationship of petrographic suites in Hawaii: Crust of the Pacific Basin, Geophysical Monograph no. 6, p. 187–195.

———1964, Chemical composition of Hawaiian lavas: Journal of Petrology, v. 5, p. 82–133.

Macdonald, G.A., and Orr, J.B., 1950, The 1949 summit eruption of Mauna Loa, Hawaii: U.S. Geological Survey Bulletin 974–A, p. 1–31.

Malahoff, A., McMurtry, G.M., Wiltshire, J.C., and Yeh, H.W., 1982, Geology and chemistry of hydrothermal deposits from active submarine volcano Loihi, Hawaii: Nature, v. 298, p. 234–239.

May, R.J., 1979, Thermoluminescence dating of Hawaiian basalt: U.S. Geological Survey Professional Paper 1095, 47 p.

McDougall, Ian, 1964, Potassium-argon ages from lavas of the Hawaiian Islands: Geological Society of America Bulletin, v. 75, p. 107–128.

McDougall, Ian, and Swanson, D.A., 1972, Potassium-argon ages of lavas from the Hawi and Pololu Volcanic Series, Kohala Volcano, Hawaii: Geological Society of America Bulletin, v. 83, p. 3731–3738.

Moore, J.G., 1964, Giant submarine landslides on the Hawaiian Ridge: U.S. Geological Survey Professional Paper 501–D, p. D95–D98.

———1965, Petrology of deep-sea basalt near Hawaii: American Journal of Science, v. 263, p. 40–52.

———1970, Relationship between subsidence and volcanic load, Hawaii: Bulletin Volcanologique, v. 34, p. 562–576.

———1975, Mechanism of formation of pillow lava: American Scientist, v. 63, p. 269–277.

Moore, J.G., and Ault, W.U., 1965, Historic littoral cones in Hawaii: Pacific Science, v. 19, p. 3–11.

Moore, J.G., Clague, D.A., and Normark, W.R., 1982, Diverse basalt types from Loihi Seamount, Hawaii: Geology, v. 10, p. 88–92.

Moore, J.G., and Fiske, R.S., 1969, Volcanic substructure inferred from dredge samples and ocean-bottom photographs, Hawaii: Geological Society of America Bulletin, v. 80, p. 1191–1202.

Moore, J.G., and Fornari, D.J., 1984, Drowned reefs as indicators of the rate of subsidence of the island of Hawaii: Journal of Geology, v. 92, p. 752–759.

Moore, J.G., and Koyanagi, R.Y., 1969, The October 1963 eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 614-C, 13 p.

Moore, J.G., and Krivoy, H.L., 1964, The 1962 flank eruption of Kilauea Volcano and structure of the east rift zone: Journal of Geophysical Research, v. 69, p. 2033–2045.

Moore, J.G., and Moore, G.W., 1984, Deposit from a giant wave on the Island of Lanai, Hawaii: Science, v. 226, p. 1312–1315.

Moore, J.G., Phillips, R.L., Grigg, R.W., Peterson, D.W., and Swanson, D. A., 1973, Flow of lava into the sea, 1969–1971, Kilauea Volcano, Hawaii: Geological Society of America Bulletin, v. 84, p. 537–546.

Moore, J.G., and Reed, R.K., 1963, Pillow structures of submarine basalts east of Hawaii: U.S. Geological Survey Professional Paper 475–B, p. B153–B157.

Moore, R.B., 1981, Preliminary geologic map of the Kapoho quadrangle, Hawaii: U.S. Geological Survey Open-File Report 81–947, scale 1:24,000.

———1983, Distribution of differentiated tholeiitic basalt on the lower east rift zone of Kilauea Volcano, Hawaii: a possible guide to geothermal exploration: Geology, v. 11, p. 136–140.

Moore, R.B., Helz, R.T., Dzurisin, D., Eaton, G.P., Koyanagi, R.Y., Lipman, P.W., Lockwood, J.P., and Puniwai, G.S., 1980, The 1977 eruption of Kilauea Volcano, Hawaii: Journal of Volcanology and Geothermal Research, v. 7, p. 189–210.

Murata, K.J., and Richter, D.H., 1966, Chemistry of the lavas of the 1959–60 eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 537–A, 26 p.

Peck, D.L., and Kinoshita, W.T., 1976, The eruption of August 1963 and the formation of Alae lava lake, Hawaii: U.S. Geological Survey Professional Paper 935–A, 33 p.

Peterson, D.W., 1971, Petroleum potential of Hawaii, *in* Cram, I. H., ed., Future Petroleum Provinces of the United States: American Association of Petroleum Geologists Memoir 15, p. 161–169.

———1976, Processes of volcanic island growth, Kilauea Volcano, Hawaii: International Association of Volcanology and Chemistry of the Earth's Interior, Proceedings of the Symposium on Andean and Antarctic Volcanology Problems, Special Series, p. 172–189.

Peterson, D.W., Christiansen, R.L., Duffield, W.A., Holcomb, R.T., and Tilling, R.I., 1976, Recent activity of Kilauea Volcano, Hawaii, *in* Gonzales-Ferran, O., ed., International Association Volcanology and Chemistry of the Earth's Interior, Symposium on Andean and Antarctic Volcanology Problems, 1974, Santiago, Chile, Proceedings: p. 646–656.

Peterson, D.W., and Tilling, R.I., 1980, Transition of basaltic lava from pahoehoe to aa, Kilauea Volcano, Hawaii: field observations and key factors: Journal of Volcanology and Geothermal Research, v. 7, p. 271–293.

Porter, S.C., 1972, Buried caldera of Mauna Kea Volcano, Hawaii: Science, v. 175, p. 1458–1460.

———1979a, Hawaiian glacial ages: Quaternary Research, v. 12, p. 161–187.

———1979b, Quaternary stratigraphy and chronology of Mauna Kea, Hawaii: a 380,000-yr record of mid-Pacific volcanism and ice-cap glaciation: Geological Society of America Bulletin, Part II, v. 90, p. 980–1093.

Porter, S.C., Stuiver, M., and Yang, I.C., 1977, Chronology of Hawaiian glaciations: Science, v. 195, p. 61–63.

Powers, H.A., 1935, Differentiation of Hawaiian lavas: American Journal of Science, 5th series, v. 30, p. 57–71.

———1948, A chronology of the explosive eruptions of Kilauea: Pacific Science, v. 2, p. 278–292.

———1955, Composition and origin of basaltic magma of the Hawaiian islands: Geochimica et Cosmochimica Acta, v. 7, p. 77–107.

Powers, Sidney, 1916, Explosive ejectamenta of Kilauea: American Journal of Science, 4th series, v. 41, p. 227–244.

———1920, Notes on Hawaiian petrology: American Journal of Science, 4th series, v.50, p. 256–280.

Rhodes, J.M., 1983, Homogeneity of lava flows: chemical data for historic Mauna Loan eruptions: Journal of Geophysical Research, v. 88, suppl. (2), p. A869–A879.

Richter, D.H., Ault, W.U., Eaton, J.P., and Moore, J.G., 1964, The 1961 eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 474–D, 34 p.

Richter, D.H., and Eaton, J.P., 1960, The 1959–60 eruption of Kilauea Volcano: New Scientist, v. 7, p. 994–997.

Richter, D.H., Eaton, J.P., Murata, K.J., Ault, W.U., and, Krivoy, H.L., 1970, Chronological narrative of the 1959–60 eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 539–E, 73 p.

Stearns, H.T., 1926, the Keaiwa or 1823 lava flow from Kilauea Volcano, Hawaii: Journal of Geology, v. 34, p. 336–351.

———1940, Four-phase volcanism in Hawaii [abs]: Geological Society of America Bulletin, v.51, p. 1947–1948.

———1946, Geology of the Hawaiian Islands: Hawaii Division of Hydrography, Bulletin 8, 105 p. (2nd printing, 1967, with supplement, 112 p.).

———1966, Geology of the State of Hawaii: Palo Alto, Ca., Pacific Books, 266 p.

———1978, Quaternary shorelines in the Hawaiian Islands: Bernice P. Bishop Museum Bulletin 237, 57 p.

Stearns, H.T., and Clark, W.O., 1930, Geology and water resources of the Kau District, Hawaii: U.S. Geological Survey Water-Supply Paper 616, 194 p.

Stearns, H.T., and Macdonald, G.A., 1946, Geology and ground-water resources of the Island of Hawaii: Hawaii Division of Hydrography, Bulletin 9, 363 p.

Stone, J.B., 1926, The products and structure of Kilauea: B.P. Bishop Museum, Bulletin 33, 59 p.

Swanson, D.A., 1972, Magma supply rate at Kilauea Volcano, 1952–1971: Science v. 175, p. 169–170.

Swanson, D.A., and Christiansen, R.L., 1973, Tragic base surge in 1790 at

Kilauea Volcano: Geology, v. 1, p. 83–86.

Swanson, D.A., Duffield, W.A., and Fiske, R. S., 1976a, Displacement of the south flank of Kilauea Volcano: the result of forceful intrusion of magma into the rift zones: U.S. Geological Survey Professional Paper 963, 39 p.

Swanson, D.A., Duffield, W.A., Jackson, D.B., and Peterson, D.W., 1979, Chronological narrative of the 1969–71 Mauna Ulu eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 1056, 55 p.

Swanson, D.A., Jackson, D.B., Duffield, W.A., and Peterson, D.W., 1971, Mauna Ulu eruption, Kilauea Volcano: Geotimes, v. 16, no. 5, p. 12–16.

Swanson, D.A., Jackson, D.B., Koyanagi, R.Y., and Wright, T.L., 1976b, The February 1969 east rift eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 891, 30 p.

Tilley, C.E., 1950, Some aspects of magmatic evolution: Quarterly Journal of the Geological Society of London, v. 106, p. 37–61.

Tilling, R.I., Koyanagi, R.Y., Lipman, P.W., Lockwood, J.P., Moore, J.G., and Swanson, D.A., 1976, Earthquake and related catastrophic events, Island of Hawaii, November 29, 1975: A preliminary report: U.S. Geological Survey Circular 740, 33 p.

Thorarinsson, S., 1967, Surtsey: New York, Viking Press, 47 p.

Unger, J.D., and Ward, P.L., 1979, A large, deep Hawaiian earthquake—the Honomu, Hawaii event of April 26, 1973: Seismological Society of America Bulletin, v. 69, p. 1771–1781.

Vancouver, G., 1798, A voyage of discovery to the north Pacific Ocean: New York, Da Capo Press (reprinted 1967), v. 3.

Washington, H.S., 1923a, Petrology of the Hawaiian Islands: I. Kohala and Mauna Kea, Hawaii: American Journal of Science, 5th series, v. 5, p. 465–502.

———1923b, Petrology of the Hawaiian Islands: II. Hualalai and Mauna Loa: American Journal of Science, 5th series, v. 6, p. 100–126.

———1923c, Petrology of the Hawaiian Islands: III. Kilauea and general petrology of Hawaii: American Journal of Science, 5th series, v. 6, p. 338–367.

Wentworth, C.K., 1938, Ash formations of the island Hawaii: Hawaiian Volcano Observatory, 3rd Special Report, 173 p.

Wentworth, C.K., and Powers, W.E., 1941, Multiple glaciation of Mauna Kea, Hawaii: Geological Society of America Bulletin, v. 52, p. 1193–1218.

Wilkes, C., 1845, Narrative of the U.S. Exploring Expedition, 1838–1842, Philadelphia, Lea and Blanchard, v. 4, p. 87–231.

Wright, T.L., 1971, Chemistry of Kilauea and Mauna Loa lava in space and time: U.S. Geological Survey Professional Paper 735, 39 p.

———1973, Magma mixing as illustrated by the 1959 eruption, Kilauea Volcano, Hawaii: Geological Society of America Bulletin, v. 84, p. 849–858.

———1984, Origin of Hawaiian tholeiite: a metasomatic model: Journal of Geophysical Research, v. 89, p. 3233–3252.

Wright, T.L., and Fiske, R.S., 1971, Origin of the differentiated and hybrid lavas of Kilauea Volcano, Hawaii: Journal of Petrology, v. 12, p. 1–65.

Wright, T.L., Kinoshita, W.T., and Peck, D.L., 1968, March 1965 eruption of Kilauea Volcano and the formation of Makaopuhi lava lake: Journal of Geophysical Research, v. 73, p. 3181–3205.

Wright, T.L., Swanson, D.A., and Duffield, W.A., 1975, Chemical compositions of Kilauea east-rift lava, 1968–1971: Journal of Petrology, v. 16, p. 110–133.

Wright, T.L., and Tilling, R.I., 1980, Chemical variations in Kilauea eruptions 1971–1974: American Journal of Science, v. 280-A, p. 777–793.