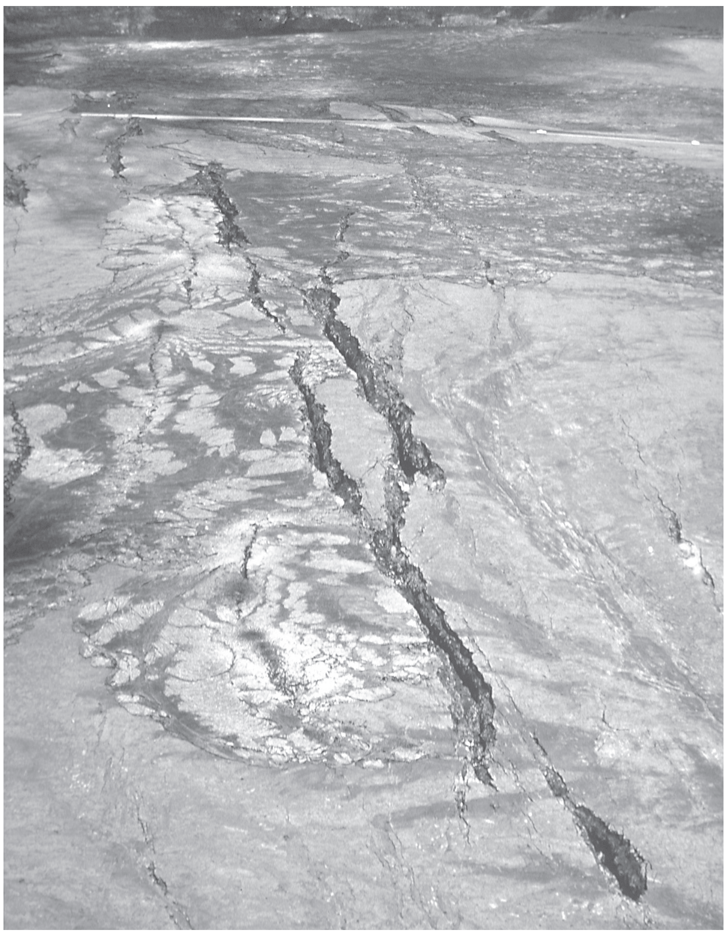
USGS
science for a changing world

Geologic Map of the Summit Region of Kīlauea Volcano, Hawaii

By Christina A. Neal and John P. Lockwood



Aerial view of some of the prominent fissures within the southwest rift zone of Kīlauea Volcano. The dark lava erupted from these fissures in September 1971. (Photograph by J.D. Griggs.)

Pamphlet to accompany
Geologic Investigations Series I–2759

2003

U.S. Department of the Interior
U.S. Geological Survey

DESCRIPTION

The area covered by this map includes parts of four U.S. Geological Survey 7.5´ topographic quadrangles (Kīlauea Crater, Volcano, Ka‘u Desert, and Makaopuhi). It encompasses the summit, upper rift zones, and Koa‘e Fault System of Kīlauea Volcano and a part of the adjacent, southeast flank of Mauna Loa Volcano (fig. 1).

The map is dominated by products of eruptions from Kīlauea Volcano, the southernmost of the five volcanoes on the Island of Hawai‘i and one of the world's most active volcanoes (fig. 1.) At its summit (1,243 m) is Kīlauea Crater, a 3 km-by-5 km collapse caldera (fig. 2, on map sheet) that formed, possibly over several centuries, between about 200 and 500 years ago. Radiating away from the summit caldera are two linear zones of intrusion and eruption, the east and the southwest rift zones. Repeated subaerial eruptions from the summit and rift zones have built a gently sloping, elongate shield volcano covering approximately 1,500 km^2. Much of the volcano lies under water; the east rift zone extends 110 km from the summit to a depth of more than 5,000 m below sea level (Moore, 1971; Holcomb and others, 1988); whereas the southwest rift zone has a more limited submarine continuation. South of the summit caldera, mostly north-facing normal faults and open fractures of the Koa‘e Fault System extend between the two rift zones. The Koa‘e Fault System is interpreted as a tear-away structure that accommodates southward movement of Kīlauea's flank in response to distension of the volcano perpendicular to the rift zones (Duffield, 1975). Farther to the south and outside the map area, the large normal fault scarps of the Hilina Pali are structures related to the seaward subsidence of Kīlauea's mobile south flank (Stearns and Clark, 1930; Swanson and others, 1976).

The northwest corner of this map covers part of the southeast flank of Mauna Loa Volcano, the most voluminous volcano on Earth. Lava flows from Mauna Loa encroach upon and are diverted by the Kīlauea edifice (Lockwood and others, 1988). The summit of Mauna Loa lies 30 km west-northwest of Kīlauea caldera and reaches 4,164 m above sea level. Like Kīlauea, Mauna Loa is characterized by a summit caldera and two radial rift zones, the northeast and southwest rift zones (fig. 1). Additionally, radial fissure vents are present on the northwest flank (Lockwood and Lipman, 1987). Of the two rift zones, only the southwest rift zone continues offshore as a conspicuous ridge extending an additional 50 km to water depths of about 4,000 m. Major flank fault systems include the Kealakekua Fault System on the western flank, the Kahuku Fault along the distal southwest rift zone, and the Ka‘ōiki-Honu‘apo Fault System on the southeastern flank. These structures are related to seaward subsidence of Mauna Loa's flanks (Lipman and others, 1988; Moore and others, 1989).

This map illustrates a succession of young basaltic lava flows erupted from Kīlauea and Mauna Loa Volcanoes, as well as pyroclastic deposits erupted from Kīlauea. No interfingering of Mauna Loa and Kīlauea flows is known in this area, although interleaving of flows is seen outside the map area and should be common at depth in the border region between the two volcanoes. Because Mauna Loa's surface area is much larger than Kīlauea's, the rate at which its surface is covered by lava (about 40 percent/1,000 years [Lockwood and Lipman, 1987]) is less than Kīlauea's (about 90 percent/1,000 years [Holcomb, 1987]), and extensive remnants of older lava flows are thus preserved on the larger volcano. Mauna Loa lavas in the map area erupted from the northeast rift zone of the volcano, 10 km north of the map edge (Lockwood and others, 1988). They range in age from a few hundred years to late Pleistocene. Kīlauea flows erupted from vents within or just outside of the modern caldera or along its upper southwest rift zone and east rift zone and range in age from historic (about 1790 to 1982) to approximately 3 ka. Pyroclastic deposits shown on the map are either from phreatic and phreatomagmatic explosive eruptions or lava fountaining in Kīlauea's summit region.

GEOLOGIC MAPPING OF THE KĪLAUEA SUMMIT REGION

This work includes and updates the geologic mapping of Peterson (1967), who completed the first 1:24,000-scale geologic map of Kīlauea Crater quadrangle. It also builds upon Walker's (1969) geologic map of the Ka‘u Desert quadrangle and the reconnaissance geologic map of the entire Kīlauea edifice by Holcomb (1980, 1987). Stearns and Clark (1930) and Stearns and Macdonald (1946) made the first generalized geologic maps of the Kīlauea summit area. They defined the Puna Volcanic Series, now the Puna Basalt (Easton, 1987), to include Kīlauea's historic and prehistoric flows and pyroclastic deposits that rest on top of the Pāhala Ash, a complex volcaniclastic deposit exposed on Mauna Loa's southeast flank and in a few places on Kīlauea's south flank. For Mauna Loa, Stearns and Macdonald (1946) defined the Ka‘u Volcanic Series, now the Ka‘u Basalt (Easton, 1987), as lava flows younger than the Pāhala Ash.

The sequence and map distribution of historic flows within Kīlauea Caldera during the period 1823 to 1961 were previously compiled by Peterson (1967). This map updates the distribution of historic lava flows and delineates additional prehistoric eruptive units. We have made only minor changes to the pre-1971 historic flows mapped by Peterson (1967).

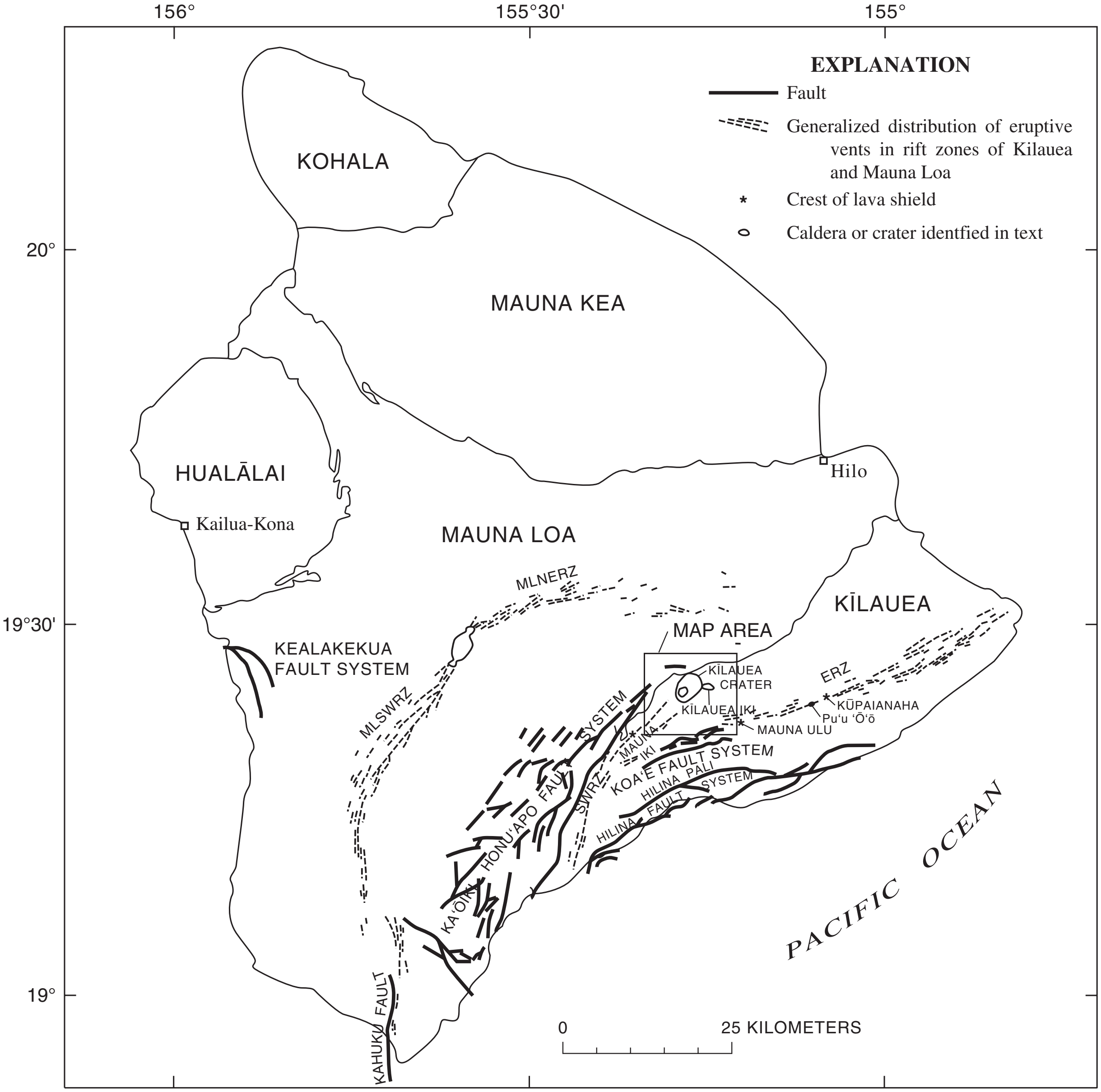


Figure 1. Map showing the five volcanoes that form the Island of Hawai'i, rift zones and major subaerial structures of Mauna Loa and Kīlauea Volcanoes, and the area covered by this map. SWRZ, southwest rift zone of Kīlauea Volcano; ERZ, east rift zone of Kīlauea Volcano; MLNERZ, northeast rift zone of Mauna Loa Volcano; MLSWRZ southwest rift zone of Mauna Loa Volcano.

Geology was primarily mapped on aerial photographs during field traverses. Linework was transferred to a base map by using a Kern PG-2 stereo plotter and, locally, by inspection. In areas of heavy vegetation along the east border of the map or thick ash cover on parts of Mauna Loa, contacts were determined by mapping sparse outcrops and by aerial photo interpretation. Due to dense vegetation and difficult access, the mapping north of the pit craters of Kīlauea's upper east rift zone and south of Highway 11 is only approximate. Similarly, lava flows of prehistoric age in the southeast corner of the map are obscured by heavy vegetation and contact relations are approximately located. Different eruptive units were recognized and correlated on the basis of lithology, surface weathering characteristics, paleomagnetic secular variation data, vesicle morphology, outcrop pattern, and degree of vegetation cover. Some contacts between widespread tube-fed pāhoehoe flows of similar appearance are difficult to follow and are shown as approximate on the map.

ROCK TYPES

Lava flows, pyroclastic deposits, and intrusive rocks portrayed on this map have physical characteristics and chemical compositions that are typical of Hawaiian tholeiitic basalt. Flow textures are pāhoehoe, ʻaʻā, and transitional varieties (Swanson, 1973). Pāhoehoe is generally smooth or hummocky, having surface roughness consisting of ropy folds and rounded, billowy toes (Wentworth and Macdonald, 1953). Some pāhoehoe flows are marked by tumuli, skylights into lava tubes, and local patches of ʻaʻā. Interior textures of pāhoehoe flows can range from dense, poorly vesicular basalt to highly vesicular basalt containing appreciable void space called shelly pāhoehoe. Slabby pāhoehoe consists of broken, upended plates of lava and is common in the near-vent area and in the transition region between pāhoehoe and ʻaʻā. Dense, hummocky, tube-fed pāhoehoe is the most common variety of lava flows found on Kīlauea. It results from long-lived eruptions and the long-distance transport of fluid lava through networks of well-insulated lava tubes (Peterson and others, 1994). Aʻāʻ flows have rough, clinkery, rubbly surfaces overlying more massive, dense interiors. There is no chemical difference between pāhoehoe and ʻaʻā; the formation of the latter is a function of cooling, degassing, and rates of internal shear in flowing lava (Peterson and Tilling, 1980). Vesicles in ʻaʻā are generally less rounded than those in pāhoehoe and often show stretching and distortion related to flowage within the plastic interior. Typical flow thicknesses are 1 to 3 m for individual pāhoehoe flows and 2 to 10 m for ʻaʻā flows.

Basalts from Kīlauea and Mauna Loa Volcanoes are generally aphyric to moderately porphyritic and may contain megascopic phenocrysts of olivine and calcic plagioclase and microscopic phenocrysts of clinopyroxene. The groundmass consists of a similar phenocryst assemblage in addition to glass and minor magnetite, ilmenite, and apatite. Mauna Loa basalts contain rare hypersthene. Most flows in this map area have less than 10 percent by volume phenocrysts, although a few picritic flows have as much as 30 percent olivine. Fresh samples are gray to black and are darker with increasing glass content.

PYROCLASTIC DEPOSITS

Pyroclastic or fragmental volcanic deposits in the Kīlauea summit area include a large reticulite (pumice) blanket formed during high lava fountaining episodes of the 1959 Kīlauea Iki eruption (Richter and others, 1970) and at least three complex sequences of lithic and vitric tephra produced by phreatomagmatic eruptions at Kīlauea's summit. These are the A.D. 1790 Keanakākoʻi Ash Member of the Puna Basalt, the 2.1 to 2.8 ka Uwēkahuna Ash Member of the Puna Basalt, and sparse exposures of the Pāhala Ash, a poorly understood deposit of deeply weathered tephras of mostly pre-Holocene age that cover large areas southwest of this map area.

Additional small pyroclastic deposits, including the early 19th century Golden Pumice of Sharp and others (1987) and the phreatic explosion debris from the 1924 explosions at Halemaʻumaʻu pit crater (Stearns, 1925), were not mapped due to their limited extent and poor preservation. Recent work has tentatively documented several additional tephra deposits of unknown origin surrounding the summit of Kīlauea (Dzurisin and others, 1995). These deposits are exposed only beneath surface flows in the map area and are not indicated on this map.

FAULTS

Four sets of normal faults are depicted in the map area. (1) The buried Kaʻōiki-Honuʻapo Fault scarps at the northwest edge of the map are related to subsidence of Mauna Loa's southeast flank (fig. 1; Lipman, 1980; Endo, 1985). (2) Faults related to Kīlauea's summit caldera are generally concentric around the modern crater and principally reflect normal faulting related to prehistoric summit collapse. With the exception of a few segments near Keanakākoʻi Crater and possibly northwest of the caldera rim (McPhie and others, 1990), most caldera-concentric faults are buried or draped by historic lava flows or the A.D. 1790 Keanakākoʻi Ash Member. (3) In the southern part of the map, mostly north-facing normal faults having offsets of as much as 20 m are part of the Koaʻe Fault System, which is related to southward movement of Kīlauea's flank and extension of the volcano perpendicular to the rift zones (Duffield, 1975). (4) Small-offset (less than 2 to 3 m) normal faults are associated with the upper southwest rift zone.

CRACKS AND NON-ERUPTIVE FISSURES

The summit and upper rift zones of Kīlauea Volcano are broken by numerous cracks and open fractures that generally trend parallel to the dominant local structure. They range in size from hairline cracks to gaping fissures as much as 5 m wide and 30 m deep. In the upper southwest rift zone, some cracks are mantled by historic lavas. Only the larger cracks and fissures are shown on this map. They formed during intrusions, significant earthquakes, calving of steep crater walls, and motion along the Koaʻe and caldera-bounding faults. Where densely spaced or anastomosing, cracks and faults are necessarily generalized for clarity. Additionally, many unmapped cracks and fissures occur in the heavily vegetated area of the upper east rift zone. De St. Ours (1982) presents more detailed mapping of faults, cracks, and fissures of the summit area.

PIT CRATERS

Pit craters from less than 10 m to 1,000 m across are common in the summit regions and along the rift zones of young Hawaiian shield volcanoes. They form after withdrawal of magma from subsurface reservoirs and subsequent collapse of overlying rocks. Halemaʻumaʻu is the youngest pit crater within the map area and lies approximately above a 2- to 6-km-deep summit magma reservoir inferred to underlie Kīlauea Volcano (Koyanagi and others, 1974; Ryan and others, 1981). The present Halemaʻumaʻu formed during multiple collapse and lava-filling events over the past two centuries. Its most recent major collapse and widening occurred in 1924. The present walls and floor of Halemaʻumaʻu consist entirely of historic lava flows. The prominent black terrace about halfway up the wall of Halemaʻumaʻu represents the high level of lava during the 1967–68 eruption. Kīlauea Iki, the site of the 1959 eruption, is a large prehistoric pit crater at the east margin of the summit area. Keanakākoʻi, Luamanu, Puhimau, Hiʻiaka, and Pauahi Craters and the Pit Craters near Cone Crater are all prehistoric in age, but they cut surface lavas that are chiefly less than 0.75 ka. The relative paucity of pit craters along the southwest rift zone relative to the east rift zone probably reflects less frequent storage and withdrawal of magma along the southwest rift zone.

DIKES

Eighteen dikes up to 1.5 m in width, some of which may have fed prehistoric eruptions, are exposed in the north and west walls of Kīlauea caldera. They were mapped and described in detail by Casadevall and Dzurisin (1987a) and are shown schematically on this map. Only one dike has been recorded in the walls of Kīlauea Iki Crater; it is exposed at the top of the foot trail that descends from Byron Ledge at the west end of the crater, and it may be a surface-fed feature.

NEAR-VENT STRUCTURES

The morphology of near-vent structures from Hawaiian eruptions depends on the style of lava emission. Eruptions accompanied by vigorous degassing and lava fountaining result in linear, sometimes discontinuous ramparts of glassy spatter and cinder from a few meters to hundreds of meters in length. Examples are found on the caldera floor and along the upper rift zones. During the 1959 Kīlauea Iki eruption, high lava fountaining produced a localized hill of reticulite and agglutinated spatter about 70 m high. In contrast, sites of dominantly fluid lava emission unaccompanied by fountaining are marked by open fissures up to 1 m wide. These fissures are commonly mantled by lava drainback deposits and surrounded by small amounts of spatter. Roughly circular shields of pāhoehoe, tens of meters high, as much as 1 km across, and topped by collapse pits or solidified pools of lava, mark the sites of extended effusion. Following eruptions, most open fissures in the summit and upper rift zones continue to emit steam, largely meteoric in origin, for months or years. Some fissures, as well as some fractures concentric to the caldera and Halemaʻumaʻu, are sites of extensive sulfur deposition (Casadevall and Hazlett, 1983).

GEOLOGIC SUMMARY

According to the prevailing model for the growth of a Hawaiian volcano (Clague and Dalrymple, 1987), Kīlauea and Mauna Loa are in the shield-building stage of their development. This map depicts a sequence of shield-building, predominantly tholeiitic basalt lava flows from summit and rift zone vents on Kīlauea and rift zone vents on Mauna Loa. This history of effusive activity is punctuated by at least two caldera-forming episodes at the summit of Kīlauea, evidence that multiple summit collapse craters develop over the lifetime of a Hawaiian volcano. Infrequent but violent explosive eruptions that involve the interaction of the Kīlauea summit magma reservoir with groundwater or surface water are also reflected in the widespread tephra units shown on this map.

The oldest map unit, the Pāhala Ash, is a highly altered and complex sequence of primary and reworked tephras. Within the map area, the Pāhala Ash is more than 1.5 m thick in scattered kīpuka on the slope of Mauna Loa. It also mantles the older Mauna Loa lava flows in the map area. The source and mechanism of formation of the Pāhala Ash has long been uncertain (Easton, 1987) and use of the term Pāhala as a formal stratigraphic horizon has evolved considerably over time (see discussion in Wolfe and Morris, 1996; Easton, 1987 and references therein). Based on the distribution of the deposit and new glass and mineral chemistry, most researchers now agree it records a series of explosive eruptions from the Kīlauea summit area over a period of time from about 39 ka to as recently as 3 ka (Beeson and others, 1996).

Limited exposures of three Mauna Loa lava flows, two of which postdate all but the youngest parts of the Pāhala Ash, represent the period of time between >10 ka to about 3.0 ka. These Mauna Loa flows have not been recognized in the walls of Kīlauea caldera or along the lower flanks of Kīlauea. The caldera walls, however, do not currently expose flows much older than about 3.0 ka

(Hagstrum and Champion, 1995) so it is possible that the Mauna Loa flows are deeply buried beneath Kīlauea's summit. Alternatively, a topographic high may have existed near the current Kīlauea summit during all or part of the interval from about 10 to 3 ka, diverting lava flows from Mauna Loa to the northeast and southwest along a break in slope that marked a long-term boundary between the two volcanoes.

Four Mauna Loa lava flows less than 3.0 ka in age are present in the northwest corner of the map. All are derived from vents about 15 km to the northwest of the map area at an elevation of approximately 3000 m along Mauna Loa's northeast rift zone. The oldest of these is a distinctive ʻaʻā flow that mantles the Kaʻōiki Pali and was emplaced between the two recognized eruptions of the Uwēkahuna Ash Member of the Puna Basalt (Dzurisin and others, 1995). The three younger Mauna Loa lava flows overlie all Uwēkahuna Ash units but are stratigraphically below the Keanakākoʻi Ash Member of the Puna Basalt. These three lava flows consist of the distinctive fluid pāhoehoe of Keahou Ranch and two ʻaʻā flows of the Keamoku eruptions. The Keamoku lava flows are distinctive when viewed from a distance because of their dark color against the older, vegetated lava flows of Mauna Loa's southeast flank.

The oldest Kīlauea lavas exposed in the map area occur beneath the Uwēkahuna Ash Member of the Puna Basalt at the base of the west caldera wall, in the walls of Pauahi Crater, and northeast of the caldera. These lava flows erupted from the Kīlauea summit more than 2.8 ka based on the maximum age of the Uwēkahuna Ash Member (Dzurisin and others, 1995). The elevation of the unfaulted, approximately 2.8 ka Kīlauea lava flow north of the caldera suggests that the summit vents at that time were at about the same elevation as the modern Uwēkahuna Bluff.

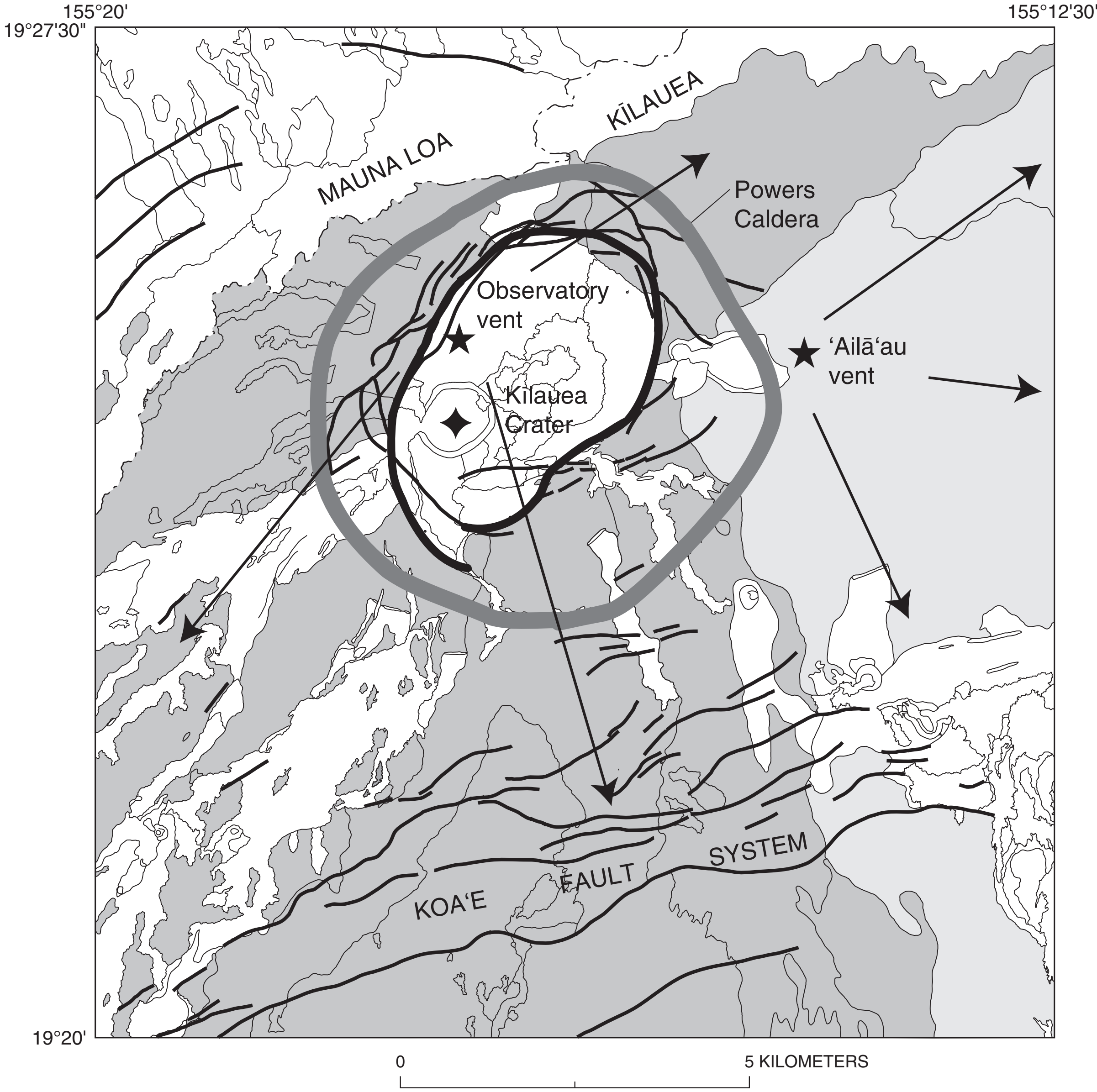
The Uwēkahuna Ash Member of the Puna Basalt, studied in detail by Dzurisin and others (1995), represents a period of violent phreatomagmatic eruptions from Kīlauea's summit. The Uwēkahuna Ash Member consists of lithic and pumiceous surge and fallout deposits from at least two principal episodes of eruptive activity between about 2.8 and 2.1 ka. On the surface of Kilauea, the deposit is largely buried by younger flows, however it is exposed near the base of Uwēkahuna Bluff, in the walls of Pit Craters in the Kaʻū Desert and, possibly, Pauahi Crater along the upper East Rift Zone. Where mapped on the surface of Mauna Loa, the Pāhala Ash usually underlies the Uwēkahuna Ash Member. Surge deposits can be traced more than 20 km away from Kīlauea caldera, attesting to the destructive potential of these energetic phreatomagmatic eruptions.

Prior to the deposition of the Uwēkahuna Ash Member, an ancestral crater named the Powers Caldera (fig. 3) existed at the summit of Kīlauea (Powers, 1948; Holcomb, 1987). The boundaries of this structure have been inferred by connecting concentric caldera fractures and faults about 2 km outside the modern rim (fig. 3; Powers, 1948; Holcomb, 1981). Evidence for its existence is based largely on (1) a fault scarp mantled by the Uwēkahuna Ash Member within Uwēkahuna Bluff (Powers, 1948) and (2) exposure of the Uwēkahuna Ash Member in the modern caldera wall at an elevation more than 100 m lower than its occurrence beneath a surface flow near the Tree Molds; this implies that a large depression existed in the summit area prior to deposition of the Uwēkahuna Ash Member.

Eruption of the Uwēkahuna Ash Member was followed by a period of caldera-filling effusive eruptions well recorded in the caldera walls (Holcomb, 1987; Casadevall and Dzurisin, 1987b). Based on the age of the oldest summit-derived, tube-fed pāhoehoe flows on the south flank, we agree with earlier workers (Swanson and others, 1976; Holcomb, 1981, 1987) that the Powers Caldera began to overflow its south rim by at least 1.2 ka (oldest ^{14}C date for flows south of the caldera) and probably earlier. Intermittent rift zone eruptions occurred during this time period outside the map area; no surface record of upper southwest rift zone or upper east rift zone eruptions of immediately post-Uwēkahuna age have been recognized.

From about 1.2 to 0.4 ka, eruption of tube-fed pāhoehoe from the summit resulted in voluminous lava flow coverage over all flanks of Kīlauea. Based on the shield-like morphology of the current western summit area, Holcomb (1981, 1987) proposed that one long-lived eruptive center, the Observatory Vent (fig. 3), existed just east of Uwēkahuna Bluff. Radiocarbon ages for lava flows that emanate from the topographic expression of the Observatory Vent (fig. 3) range from 660 to 410 yr BP, indicating that this summit vent was active for several centuries. However, it is also possible that this general site was active at least as early as about 1.2 ka when lava flows first spilled over the Powers Caldera rim. Radiocarbon ages for mapped tube-fed pāhoehoe flows south of the caldera (map units k3k, k4ok, k4ol, k4ov, k4oo, k4oy; table 1) suggest fairly continuous activity at the summit vents during this interval.

Following cessation of activity at the Observatory Vent about 0.4 ka, the locus of eruptions moved to the eastern part of the summit near Thurston Lava Tube (ʻAilāʻau vent, Holcomb, 1981; 1987). Voluminous fountain- and tube-fed pāhoehoe flows moved generally east down the flanks of Kīlauea from a topographic high that was later truncated by the collapse of Kīlauea Iki Crater. No lava flows correlated with the ʻAilāʻau vent have been mapped west of Kīlauea Iki, suggesting that during ʻAilāʻau eruptions, a topographic barrier, possibly the east flank of a lava shield marking the Observatory vent, existed just west of the present crater. Twelve radiocarbon



EXPLANATION

- Contact
- Fault
- Present Halema‘uma‘u Crater
- Inferred position of prehistoric, long-lived summit vents (Holcomb, 1987)
- Inferred boundary of Powers Caldera (after Holcomb, 1987)
- Modern summit caldera boundary
- Lavas from Observatory vent (Observatory shield)
- Lavas from ‘Ailā‘au vent (‘Ailā‘au shield)
- Generalized direction of lava flows from prehistoric summit vents
- Boundary between Mauna Loa and Kīlauea Volcanoes

Figure 3. Map of the Kīlauea summit area showing probable locations of prehistoric vents, caldera, and flows.

dates have been determined for lava flows correlated with the ‘Ailā‘au shield (k4ya; k4yo; table 1). They range in age from 230 to 620 yr BP with an average of about 370 yr BP. With fewer radiocarbon dates available, Holcomb (1981; 1987) interpreted the paleomagnetic data to indicate an older age for lavas from the ‘Ailā‘au vent. Based on new radiocarbon dating (this study; Wolfe and Morris, 1996), we conclude that ‘Ailā‘au eruptions followed the Observatory eruptions in time. However, there appears to have been no significant hiatus between eruptive activity at the Observatory and ‘Ailā‘au vents.

Few upper east and southwest rift zone eruptions can be shown to have occurred during the period of sustained activity at the two summit shields. With the exception of the ‘a‘ā flow of Keanakāko‘i and possibly eruptive products from Pu‘uhuluhulu, all prehistoric extracaldera and rift zone eruptions in this map area postdate the youngest Observatory flow and so are less than about 0.5 ka in age. Several upper east rift zone eruptions also postdate the youngest ‘Ailā‘au eruptions, although map relations in the heavily vegetated upper east rift zone are uncertain, and other interpretations are possible. Based on surface weathering, the cinder and spatter cone near Devil’s Throat is inferred to be the oldest rift zone feature in the map area.

The Koa‘e Fault System south of Kīlauea’s summit has been active for at least the last thousand years based on the ages of lava flows that were clearly deflected by Koa‘e structure (lava flows of the Observatory vent [k4oy, k4oo], Āhua [k4oa], Pu‘ukoa‘e [k4yk], and older lava flows of Kālu‘e [k3k]). The large coastline bight due south of the Koa‘e Fault System (fig. 1) may reflect a longterm structure that acts as a barrier to flows moving south from the summit region. If the Koa‘e Fault System reflects extension related to motion of Kīlauea’s south flank, it is likely to have existed for much of the volcano’s subaerial history. Dividing cumulative southward extension measured across the Koa‘e Fault System (Duffield, 1975) by the age of the Kālu‘e and the Āhua flows that enclose the zone of open ground fractures measured by Duffield, we obtain an average rate of extension of 3 to 6 cm/yr over the last approximately 0.7 ka. This rate is of the same order of magnitude as the rate of extension measured across the eastern Koa‘e Fault System for the period between 1975 and 1989 (6.8 cm/yr; Delaney and others, 1990) and suggests a constant rate of deformation in this area over at least the last 0.7 ka.

Between 0.8 ka and as recently as the 18th century, voluminous eruptions from the northeast rift zone of Mauna Loa sent lava flows down the southeast flank and onto the Kīlauea edifice in the northwest corner of the map. Topography diverted these lava flows southwest along the slight depression of the Kīlauea-Mauna Loa boundary. This boundary saddle, however, is filling in; future eruptions from Mauna Loa’s northeast rift zone have the potential of traveling farther onto the flanks of Kīlauea.

Details of the formation of the modern Kīlauea caldera and Kīlauea Iki Crater are poorly constrained in time. It is likely that collapse was progressive over several centuries, beginning toward the end of activity at the Observatory vent about 0.5 ka and continuing after cessation of the ‘Ailā‘au Puna Basalt (Swanson and Christiansen, 1973), a thick sequence of pyroclastic surge, fallout, and lava fountaining debris exposed in the southeast caldera walls (McPhie and others, 1990) and extensively around the summit. With the exception of caldera faults near Keanakāko‘i Crater, most major caldera bounding scarps are draped by 1790 deposits indicating that major caldera structures were in place prior to the phreatomagmatic eruptions.

By 1823, a lava lake within Kīlauea caldera was the site of sustained activity at Kīlauea’s summit (Ellis, 1827). Halema‘uma‘u pit crater developed as one of several separate lava lakes on the caldera floor and became the dominant site of activity by the late 1830’s. For most of the next century, a complex filling, draining, and overflowing of lava lakes in Halema‘uma‘u formed a growing lava shield within the caldera (fig. 2; see summaries of activity in Peterson and Moore, 1987 and Holcomb, 1987). Major subsidence events occurred in conjunction with large rift zone eruptions and intrusions such as the 1840 lower east rift zone eruption (Coan, 1841) and the 1919–20 Mauna Iki eruption on the southwest rift zone (Rowland and Munro, 1993). A large earthquake in 1868 caused a significant lowering of the caldera floor and widening of Halema‘uma‘u; a related small eruption from a site near Byron Ledge covered the floor of Kīlauea Iki Crater with lava (Hitchcock, 1909). Minor summit eruptions on the east caldera wall and Byron Ledge also occurred in 1832 and 1877. A previously undocumented, post-Keanakāko‘i lava flow southwest of Pu‘ukoa‘e most likely erupted in the early 1800’s. This small pāhoehoe pad may have erupted coincident with significant earthquakes in 1823 or 1868, or possibly in conjunction with eruption of the golden pumice between 1820 and 1823 (Sharp and others, 1987; D. A. Swanson and T.L. Wright, oral commun., 1997).

In 1924, a drastic lowering of the lava column in Halema‘uma‘u followed a large intrusion into the lower east rift zone, possibly accompanied by a submarine eruption. Resulting phreatic and weakly phreatomagmatic blasts from Halema‘uma‘u over a period of 17 days accompanied a deepening and widening of the pit crater and distributed blocks and ash locally around the summit area (Stearns, 1925). Lava lake activity resumed at Halema‘uma‘u following the 1924 eruption. Episodic filling and draining of the lava lake with no overflows occurred until a brief eruption on the floor of the caldera in 1954. The 1954 eruption was followed by a period of accelerated east rift zone activity and few eruptions in the summit area. In 1959, multiple episodes of high lava fountaining from Kīlauea Iki produced a blanket of pumice southwest of the crater and filled Kīlauea Iki with a lava lake 135 m thick. After a brief eruption within Halemaʻumaʻu in 1961, a lava lake reappeared in 1967–68 during the last period of sustained activity at Kīlauea's summit.

Brief east rift zone eruptions in 1968 and early 1969 were followed by an extended eruption from a series of vents along the upper east rift zone. Nearly continuous eruption from 1969–1974 produced a 120-m-high lava shield, Mauna Ulu (fig. 1; Swanson and others, 1979; Tilling and others, 1987). Lava flows from this eruption destroyed a large section of Chain of Craters Road and reached the sea several times between 1969 and 1973. Interruptions in Mauna Ulu activity coincided with brief fissure eruptions in the caldera and the upper southwest rift zone in 1971. Brief eruptions in the caldera and upper southwest and east rift zones also occurred in 1974 after the Mauna Ulu eruption ended (Peterson and others, 1976).

On November 29, 1975, an M 7.2 earthquake on Kīlauea's south flank was followed 45 minutes later by a sporadic 17-hour eruption within Halemaʻumaʻu and on the caldera floor just east of Halemaʻumaʻu (Tilling and others, 1976). The following six years saw frequent intrusive activity along both rift zones punctuated by brief eruptions along the middle east rift zone in 1977 (Moore and others, 1980; Dzurisin and others, 1984) and in the Pauahi Crater area in 1979 (Banks and others, 1981). The most recent eruptions in the summit caldera occurred in April and September of 1982 (Banks and others, 1983). Since January 3, 1983, eruptive activity has been nearly continuous along a portion of the middle east rift zone producing a cinder and spatter cone called Puʻu ʻŌʻō, a 60-m-high lava shield named Kūpaianaha (fig. 1), and a lava flow field that covers more than 80 km^2. Tube-fed lava flows from this eruption, the longest Hawaiian eruption in historic times, reached the sea in 1986 (Wolfe and others, 1988; Heliker and Wright, 1991; Mattox and others, 1993; Mangan and others, 1995).

On November 16, 1983, a Ms 6.6 earthquake on the southeast flank of Mauna Loa caused numerous rockfalls within Kīlauea Caldera (Buchanan-Banks, 1987). The largest of these rockfall accumulations are shown as talus on the map.

MAP UNIT SYMBOLS

Historic lava flows and pyroclastic deposits are indicated on the map by the year or, for those years with multiple events, the month and year of eruption. Prehistoric map units are designated by a three or four letter symbol representing unit origin, age (table 2), and some distinctive characteristic related to geography, morphology, or lithology as explained in the Description of Map Units. Symbols that begin with k and m are Kīlauea lava flows or pyroclastic deposits and Mauna Loa lava flows, respectively. Numerical representations of unit age are explained below.

AGE ASSIGNMENT

Hawaiians are thought to have arrived on the island of Hawaiʻi about 1.5 ka (Kirch, 1985), but oral accounts of eruptions prior to about A.D. 1790 are few and difficult to interpret. For these prehistoric eruptions, radiocarbon dating of carbonized vegetation preserved under and, rarely, within lava flows and pyroclastic deposits has been the most critical technique for accurate age assignment (Kelley and others, 1979; Lockwood and Lipman 1980; Rubin and others, 1987; Lockwood, 1995). Radiocarbon sample locations and ages are shown on the map and listed in table 1. Ages reported are derived from laboratory radiocarbon dates and have not been converted to calendar equivalents (Stuiver and Reimer, 1993; Lockwood, 1995). For multiply-dated lava flows, ages reported in the Correlation of Map Units represent weighted averages and standard errors for dates considered reliable (method from Bevington, 1969; see usage in Dzurisin and others, 1995, Appendix B and Lockwood, 1995, Appendix A). Ages for the complex Pahala Ash unit are not reported here. Readers are referred to Kelly and others, 1979; Easton, 1987; Wolfe and Morris, 1996; and Beeson and others, 1996 for radiocarbon dating results for the Pahala Ash.

Additional methods of assigning ages to map units include superposition relationships, paleomagnetic secular variation (Holcomb and others, 1986; Hagstrum and Champion, 1995), and weathering characteristics (Lipman and Swenson, 1984). Based on these criteria, prehistoric map units have been arranged into age groups following the symbology of Wolfe and Morris, 1996 (table 1).

ACKNOWLEDGMENTS

We thank Don Peterson for sharing important observations of the Kīlauea summit area, Bob Christiansen for insights and unpublished data regarding the Keanakākoʻi Ash, Duane Champion for paleomagnetic expertise, and Meyer Rubin for radiocarbon expertise. Significant contributions of Robin Holcomb to our understanding of the evolution of Kīlauea are respectfully acknowledged. Ed Wolfe and Jean Morris of the Island of Hawaiʻi Geologic Map Project provided critical support and encouragement. George Ulrich created the original map base and conceived the idea for a new geologic map of the Kīlauea summit area. We are also grateful to Bobby Camara for perceptive questions and assistance with proper use of the Hawaiian language and Stefan Kempe for insights into Kīlauea's lava tubes. This map would not have been possible without the creativity, good humor, and technical expertise of Peggy Bruggman, Dillon Dutton, Tracey Felger, Ellen Lougee, Sandy Margriter, Lori Moore, Patrick Showalter, and Carl Wentworth. Pete Lipman and Don Swanson provided essential encouragement and guidance during the final stages of map preparation. Reviewers Dick Moore, Don Peterson, and Don Swanson are gratefully acknowledged.

Table 1. *Summary of radiocarbon ages for lava flows in the summit area of Kīlauea Volcano. Locations for samples within map area extracted from digital database and rounded to nearest hundredth of a minute. *, sample location outside map area; <, less than.*

Map unit	Laboratory number	Latitude (W.)	Longitude (N.)	Laboratory/ analyst	^{14}C age (radiocarbon years B.P.)	References
m4y	W3871	19°26.72´	155°19.10´	a	230±60	1,2
	*W4360	19°39.62´	155°20.68´	a	300±60	1,4
m4o	*W3879	19°27.80´	155°17.07´	a	830±60	1,2
	W3880	19°27.32´	155°17.21´	a	530±60	1,2,4
	*W4341	19°30.48´	155°20.60´	a	330±60	1,4
	W4367	19°26.75´	155°16.57´	a	570±70	1,4
	*W4845	19°28.28´	155°17.73´	a	640±70	1,4
m3	*W4345	19°29.57´	155°20.62´	a	760±70	1
m2	W3876	19°27.33´	155°17.61´	a	2,190±70	1,2,3
	W4831	19°27.33´	155°17.61´	a	2,340±70	1,3
m1o	*W3853	19°25.18´	155°20.33´	a	8,550±100	1,4
	W4803	19°26.03´	155°19.74´	a	8,740±100	1,4
k4ya	*W3881	19°32.78´	155°05.88´	a	260±70	1,2,4
	*W3941	19°35.27´	155°01.10´	a	450±60	1,2,4
	W4337	19°20.18´	155°13.42´	a	620±70	1,2,4
	*W4661	19°33.15´	155°01.03´	a	320±70	1,4
	*W4184	19°19.80´	155°12.98´	a	<200[1]	1,2
	*W5110	19°19.02´	155°13.12´	a	230±60	1,2,4
	*W5631	19°30.47´	155°07.68´	a	580±200	4
	*W6269	19°20.19´	155°03.77´	a	350±90	4
	*WW117	19°26.17´	155°01.79´	c	320±70	4
	*WW117	19°26.17´	155°01.79´	c	340±80	4
	AA10602	19°20.30´	155°13.46´	b	400±55	5
	WW308	19°21.55´	155°14.10´	c	400±50	5
k4yo	*W4162	19°28.28´	155°10.17´	a	310±70	1
k4oy	W4998	19°26.20´	155°16.97´	a	960±60[2]	1,3
	*W5757	19°21.01´	155°23.56´	a	410±100	4
	*W5152	19°19.68´	155°19.78´	a	660±70	1,4
k4oo	*W3842	19°19.98´	155°24.33´	a	450±60	1,2,4
	*W5218	19°09.60´	155°26.83´	a	550±70	1,4
	*W5771	19°20.59´	155°23.87´	a	590±100	4
k4ov	W3870	19°26.65´	155°15.12´	a	350±60	1,2
	W3999	19°27.07´	155°14.31´	a	730±150	1,2,4
	*W5319	19°27.33´	155°12.42´	a	970±120	1,2
	W5791	19°26.84´	155°15.33´	a	1170±150	6
	W5897	19°26.40´	155°14.81´	a	550±150	4
	W6007	19°26.96´	155°15.30´	a	580±100	4
k4ol	*W5983	19°19.45´	155°14.83´	a	550±110	4
k4ok	*W4402	19°44.73´	155°08.68´	a	700±70	1,2,4
	W5785	19°20.37´	155°16.85´	a	600±100	4
	*W5973	19°19.44´	155°17.75´	a	740±100	4

Table 1. *Summary of radiocarbon ages for lava flows in the summit area of Kīlauea Volcano. Locations for samples within map area extracted from digital database and rounded to nearest hundredth of a minute. [*, sample location outside map area; <, less than] — Continued*

Map unit	Laboratory number	Latitude (W.)	Longitude (N.)	Laboratory/ analyst	^{14}C age (radiocarbon years BP)	References
	WW370	19°20.38´	155°16.81´	c	460±60	5
	*WW307	19°19.47´	155°17.75´	c	740±70	5
k3k	*W5135	19°19.77´	155°16.85´	a	1150±70	1,2,4
	*W5212	19°17.88´	155°18.63´	a	1140±70	1,4
	*W5975	19°18.37´	155°17.28´	a	900±120	4
	WW301	19°20.42´	155°16.64´	c	970±60	5
	WW302	19°21.04´	155°16.39´	c	650±60[3]	5
	*WW303	19°19.35´	155°16.85´	c	800±50	5
	*WW304	19°19.07´	155°16.82´	c	980±60	5
	*WW305	19°18.40´	155°16.69´	c	680±50[4]	5
	*WW306	19°18.35´	155°16.83´	c	320±50[5]	5
k2w	*W5345	19°27.62´	155°14.87´	a	2,770±150	1,4

Laboratory/analyst:

a Meyer Rubin, U.S. Geological Survey Radiocarbon Laboratory, Reston, Virginia
b National Science Foundation, Arizona AMS Laboratory, University of Arizona, Tucson, Arizona (accelerator mass spectrometry)
c Lawrence Livermore National Laboratory, Berkeley, California (accelerator mass spectrometry)

^{14}C age notes:

1 Anomalously young age due to possible sample contamination by modern soils
2 Age considered unreliable due to contamination by volcanogenic ^{12}C
3 Young age may date an outcrop of k4oa that is near sampling site
4 Young ages may have been caused by modern carbon contamination due to recent fire in the area

References:

1 Rubin and others, 1987
2 Holcomb, 1987
3 Dzurisin and others, 1995
4 Wolfe and Morris, 1996
5 R. Fiske, D. Swanson, and T. Rose, unpublished data
6 This study

Table 2. *Age assignment of prehistoric map units*

numerical code	estimated age in ^{14}C years B.P.
4y	200+–400
4o	400–750
3	750–1500
2	1,500–3,000
1y	3,000–5,000
1o	5,000–10,000
0	>10,000

REFERENCES CITED

Banks, N.G., Klein, F.W., Moore, R.B., Jackson, D.B., and Okamura, A.T., 1981, Kilauea Volcano's November 1979 eruption [abs.]: Eos, Transactions of the American Geophysical Union, 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, 1982 [abs.]: Eos, Transactions of the American Geophysical Union, v. 64, no. 45, p. 901–902.

Beeson, M.H., Clague, D.A., and Lockwood, J.P., 1996, Origin and depositional environment of clastic deposits in the Hilo drill hole, Hawaii: Journal of Geophysical Research, v. 101, no. B5, p. 11617–11629.

Bevington, P.R., 1969, Data reduction and error analysis for the physical sciences: New York, McGraw-Hill, 336 p.

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

Buchanan-Banks, J.M., 1987, Structural damage and ground failures from the November 16, 1983, Kaoiki earthquake, Island of Hawaii, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii, v. 2: U.S. Geological Survey Professional Paper 1350, p. 1187–1220.

Casadevall, T.J., and Hazlett, R.W., 1983, Thermal areas on Kilauea and Mauna Loa volcanoes, Hawaii: Journal of Volcanology and Geothermal Research, v. 16, p. 173–188.

Casadevall, T.J., and Dzurisin, Daniel, 1987a, Intrusive rocks of Kilauea caldera, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 377–394.

Casadevall, T.J., and Dzurisin, Daniel, 1987b, Stratigraphy and petrology of the Uwekahuna Bluff section, Kilauea Caldera, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 351–375.

Clague, D.A., and Dalrymple, G.B., 1987, The Hawaiian-Emperor volcanic chain, Part I. Geologic evolution, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 5–54.

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

Dana, J.D., 1890, Characteristics of volcanoes: London, Sampson, Low, Marston, Searle, and Rivington, Ltd., 199 p.

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

Delaney, P.T., Fiske, R.S., Miklius, Asta, Okamura, A.O., and Sako, M.K., 1990, Deep magma body beneath the summit and rift zones of Kilauea Volcano: Science, v. 247, p. 1265–1372.

Doell, R.R., and Cox, Allan, 1965, Paleomagnetism of Hawaiian lava flows: Journal of Geophysical Research, no. 14, v. 70, p. 3377–3405.

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.

Dzurisin, Daniel, Koyanagi, R.Y., and English, T.T., 1984, Magma supply and storage at Kilauea Volcano, Hawaii, 1956–1983: Journal of Volcanology and Geothermal Research, v. 21, p. 177–206.

Dzurisin, Daniel, Lockwood, J.P., Casadevall, T.J., and Rubin, Meyer, 1995, The Uwekahuna Ash Member of the Puna Basalt: Product of violent phreatomagmatic eruptions at Kilauea Volcano, Hawaii, between 2,800 and 2,100 ^{14}C years ago: Journal of Volcanology and Geothermal Research, v. 66, p. 163–184.

Easton, R.M., 1987, Stratigraphy of Kilauea Volcano, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 243–260.

Ellis, William, 1827, Journal of William Ellis: narrative of a tour of Hawaii, or Owhyhee; with remarks on the history, traditions, manners, customs, and language of the inhabitants of the Sandwich Islands: Honolulu, Advertiser Publishing Co., Ltd., 342 p. (Reprinted 1963.)

Endo, E.T., 1985, Seismotectonic framework for the southeast flank of Mauna Loa volcano, Hawaii: University of Washington, Ph.D. dissertation, 350 p.

Hagstrum, J.T., and Champion, D.E., 1995, Late Quaternary geomagnetic secular variation from historical and ^{14}C-dated lava flows on Hawaii: Journal of Geophysical Research, v. 100, no. B12, p. 24393–24403.

Hawaiian Volcano Observatory Research Association, (Volcanic Events) 1918: Hawaiian Volcano Observatory Weekly Bull., v. 6, no. 2–3, p. 23–44.

Heliker, C.C., and Wright, T.L., 1991, The Pu‘u ‘Ō‘ō-Kūpaianaha eruption of Kīlauea: Eos, Transactions of the American Geophysical Union, v. 72, p. 521–530.

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

Holcomb, R.T., 1976, Preliminary map showing products of eruptions, 1962–1974, from the upper east rift zone of Kilauea Volcano, Hawaii: U.S. Geological Survey Miscellaneous Field Studies Map MF–8111, 1:24:000.

Holcomb, R.T., 1980, Preliminary geologic map of Kilauea Volcano, Hawaii: U.S. Geological Survey Open-File Report 80–796, 2 sheets, scale 1:50,000.

Holcomb, R.T., 1981, Kilauea Volcano, Hawaii: Chronology and morphology of the surficial lava flows: U.S. Geological Survey Open-File Report 81–354, 321 p.

Holcomb, R.T., 1987, Eruptive history and long-term behavior of Kilauea volcano, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 261–350.

Holcomb, R.T., Champion, D.E., and McWilliams, M.O., 1986, Dating recent Hawaiian lava flows using paleomagnetic secular variation: Geological Society of America Bulletin, v. 97, p. 829–839.

Holcomb, R.T., Moore, J.G., Lipman, P.W., and Belderson, R.H., 1988, Voluminous submarine lava flows from Hawaiian volcanoes: Geology, v. 16, p. 400–404.

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.

Kelley, M.L., Spiker, E.C., Lipman, P.W., Lockwood, J.P., Holcomb, R.T., and Rubin, Meyer, 1979, U.S. Geological Survey, Reston, Virginia, radiocarbon dates XV: Mauna Loa and Kilauea Volcanoes, Hawaii: Radiocarbon, v. 21, no. 2, p. 306–320.

Kirch, P.V., 1985, Feathered gods and fishhooks: Honolulu, University of Hawai'i Press, 349 p.

Koyanagi, R.Y., Unger, J.D., Endo, E.T., and Okamura, A.O., 1974, Shallow earthquakes associated with inflation at the summit of Kilauea Volcano, Hawaii, *in* Gonzales-Ferran, O., ed., Symposium on Andean and Antarctic Volcanic Problems, Santiago, Chile, September 9–14, 1974, Proceedings: International Association of Volcanology and Chemistry of the Earth's Interior Special Series, p. 621–631.

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 Map I–1323, scale 1:100,000.

Lipman, P.W., Normark, W.R., Moore, J.G., Wilson, J.B., and Gutmacher, C.E., 1988, The giant submarine Alika debris slide, Mauna Loa, Hawaii: Journal of Geophysical Research, v. 93, no. B5, p. 4279–4299.

Lockwood, J.P., 1995, Mauna Loa eruptive history—the preliminary radiocarbon record, *in* Lockwood, J.P, and Rhodes, J.M., eds., Mauna Loa revealed—structure, composition, history, and hazards: Washington D.C., American Geophysical Union Monograph 92, 348 p.

Lockwood, J.P., and Lipman, P.W., 1980, Recovery of datable charcoal beneath young lavas—lessons from Hawaii: Bulletin of Volcanology, v. 43, no. 4, p. 609–615.

Lockwood, J.P., and Lipman, P.W., 1987, Holocene eruptive history of Mauna Loa Volcano, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 509–535.

Lockwood, J.P., Lipman, P.W., Petersen, L.D., and Warshauer, F.R., 1988, Generalized ages of surface lavas of Mauna Loa Volcano, Hawaii: U.S. Geological Survey Miscellaneous Field Investigations Map I–1908, scale 1:250,000.

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

Mangan, M.T., Heliker, C.C., Mattox, T.N., Kauahikaua, J.P., and Helz, R.T., 1995, Episode 49 of the Pu'u 'O'o-Kupaianaha eruption of Kilauea Volcano—breakdown of a steady-state eruptive era: Bulletin of Volcanology, v. 57, p. 127–135.

Mattox, T.N., Heliker, Christina, Kauahikaua, Jim, and Hon, Ken, 1993, Development of the 1990 Kalapana flow field, Kīlauea Volcano, Hawaii: Bulletin of Volcanology, v. 55, p. 407–413.

McPhie, Jocelyn, Walker, G.P.L., and Christiansen, R.L., 1990, Phreatomagmatic and phreatic fall and surge deposits from explosions at Kilauea Volcano, Hawaii, 1790 A.D.: Keanakakoi Ash Member: Bulletin of Volcanology, v. 52, p. 334–354.

Moore, J.G., 1971, Bathymetry and geology—east cape of Hawaii: U.S. Geological Survey Miscellaneous Field Investigations Map I–677, scale 1:62,000.

Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., and Torresan, M.E., 1989, Prodigious submarine landslides on the Hawaiian Ridge: Journal of Geophysical Research, v. 94, no. B12, p. 17,465–17,484.

Moore, R.B., Helz, R.T., Dzurisin, Daniel, 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., 1961, Magmatic differentiation in the Uwekahuna laccolith, Kilauea caldera, Hawaii: Journal of Petrology, v. 2, no. 3, p. 424–437.

Peterson, D.W., 1967, Geologic map of the Kilauea Crater Quadrangle, Hawaii: U.S. Geological Survey Quadrangle Map GQ–667, scale 1:24,000.

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., Symposium on Andean and Antarctic Volcanic Problems, Santiago, Chile, September 9–14, 1974, Proceedings: International Association of Volcanology and Chemistry of the Earth's Interior Special Series, p. 646–656.

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

Peterson, D.W., and Moore, R.B., 1987, Geologic history and evolution of geologic concepts, Island of Hawaii, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 149–190.

Peterson, D.W., Holcomb, R.T., Tilling, R.I., and Christiansen, R.L., 1994, Development of lava tubes in the light of observations at Mauna Ulu, Kilauea Volcano, Hawaii: Bulletin of Volcanology, v. 56, no. 5, p. 343–360.

Powers, H.A., 1948, A chronology of the explosive eruptions at Kilauea: Pacific Science, v. 2, no. 4, p. 278–992.

Pukui, M.K., and Elbert, S.H., 1986, Hawaiian Dictionary: Hawaiian-English, English-Hawaiian (revised and enlarged edition): Honolulu, Hawaii, University of Hawaii Press, 572 p.

Pukui, M.K., Elbert, S.H., and Mookini, E.T., 1989, Place Names of Hawaii, revised and expanded edition): Honolulu, Hawaii, University of Hawaii Press, 289 p.

Rhodes, J.M., Wenz, K.P., Neal, C.A., Sparks, J.W., and Lockwood, J.P., 1989, Geochemical evidence for invasion of Kilauea's plumbing system by Mauna Loa magma: Nature, v. 337, p. 257–260.

Richter, D.H., Eaton, J.P., Murata, K.J., Ault, W.U., and Krivoy, W.L., 1970, Chronological narrative of the 1959–60 eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 537–E, 73 p.

Rowland, S.K., and Munro, D.C., 1993, The 1919–1920 eruption of Mauna Iki, Kilauea: chronology, geologic mapping, and magma transport mechanism: Bulletin of Volcanology, v. 55, p. 190–203.

Rubin, Meyer, Gargulinski, L.K., and McGeehin, J.P., 1987, Hawaiian radiocarbon dates, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 213–242.

Ryan, M.P., Koyanagi, R.Y., and Fiske, R.S., 1981, Modeling the three-dimensional structure of macroscopic magma transport systems: Applications to Kilauea Volcano, Hawaii: Journal of Geophysical Research, v. 86, no. B8, p. 7111–7129.

de St.-Ours, P.J., 1982, Map of tectonic features of the Kilauea Volcano summit region, Hawaii: U.S. Geological Survey Miscellaneous Field Studies Map MF–1368, scale 1:24,000.

Sharp, R.P., Dzurisin, Daniel, and Malin, M.C., 1987, An early 19th century reticulite pumice from Kilauea Volcano, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 395–404.

Stearns, H.T., 1925, The explosive phase of Kilauea Volcano, Hawaii in 1924: Bulletin of Volcanology, v. 2, p. 193–209.

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., 3 folded maps in pocket.

Stearns, H.T., and Macdonald, G.A., 1946, Geology and groundwater resources of the Island of Hawaii: Hawaii Division of Hydrography Bulletin 9, 363 p., 2 folded maps in pocket.

Swanson, D.A., 1973, Pahoehoe flows from the 1969–1971 Mauna Ulu eruption, Kīlauea Volcano, Hawaii: Geological Society of America Bulletin, v. 84, p. 615–626.

Swanson, D.A., and Christiansen, R.L., 1973, Tragic base surge in 1790 at Kilauea Volcano, Hawaii: Geology, v. 1, p. 83–86.

Swanson, D.A., Duffield, W.A., and Fiske, R.S., 1976, 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 1969–1971 Mauna Ulu eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 1056, 55 p.

Tilling, R.I., Koyanagi, R.Y., Lipman, P.W., Lockwood, J.P., 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.

Tilling, R.I., Christiansen, R.L., Duffield, W.A., Endo, E.T., Holcomb, R.T., Koyanagi, R.Y., Peterson, D.W., and Unger, J,D., 1987, The 1972–1974 Mauna Ulu eruption, Kilauea Volcano: An example of quasi-steady-state magma transfer, *in* Decker, R.W., Wright, T.L., and Stauffer, P.W., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 405–469.

U.S. Department of Agriculture (Volcanic Events), 1919, Monthly Bulletin of the Hawaiian Volcano Observatory, v. 7, nos. 2–4, p. 13–56.

U.S. Department of Agriculture (Volcanic Events), 1921, Monthly Bulletin of the Hawaiian Volcano Observatory, v. 9, no. 3, p. 33–50.

Volcano House Register, 1873–1885, 1885–1891, 1891–1898, (Records of accounts by visitors to the Volcano House, Hawaii National Park, Hawaii from 1865–1955), v. 2,3,5.

Walker, G.W., 1969, Geologic Map of the Kau Desert Quadrangle, Hawaii: U.S. Geological Survey Quadrangle Map GQ–827, scale 1:24,000.

Wentworth, C.K., and Macdonald, G.A., 1953, Structures and forms of basaltic rocks in Hawaii: U.S. Geological Survey Bulletin 994, 98 p.

Wolfe, E.W., Neal, C.A., Banks, N.G., and Duggan, T.J., 1988, Geologic observations and chronology of eruptive events, *in* Wolfe, E.W., ed., The Puu Oo eruption of Kilauea Volcano, Hawaii, episodes 1–20: U.S. Geological Survey Professional Paper 1463, p. 1–97.

Wolfe, E.W., and Morris, Jean, compilers, 1996, Geologic map of the Island of Hawaii: U.S. Geological Survey Miscellaneous Field Investigations Map I–2524, 3 sheets, scale 1:100,000.

Wright, T.L., 1971, Chemistry of Kilauea and Mauna Loa in space and time: U.S. Geological Survey Professional Paper 735, 40 p.