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Volcanic geology and eruption frequency, lower east rift zone of Kilauea volcano, Hawaii

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Abstract. Detailed geologic mapping and radiocarbon dating of tholeiitic basalts covering about 275 km^2 on the lower east rift zone (LERZ) and adjoining flanks of Kilauea volcano, Hawaii, show that at least 112 separate eruptions have occurred during the past 2360 years. Eruptive products include spatter ramparts and cones, a shield, two extensive lithic-rich tuff deposits, aa and pahoehoe flows, and three littoral cones. Areal coverage, number of eruptions and average dormant interval estimates in years for the five age groups assigned are: (I) historic, i.e. A D 1790 and younger: 25%, 5, 42.75; (II) 200–400 years old: 50%, 15, 14.3: (III) 400–750 years old: 20%, 54, 6.6; (IV) 750–1500 years old: 5%, 37, 20.8; (V) 1500–3000 years old: < 1%, 1, unknown. At least 4.5–6 km^3 of tholeiitic basalt have been erupted from the LERZ during the past 1500 years. Estimated volumes of the exposed products of individual eruptions range from a few tens of cubic meters for older units in small kipukas to as much as 0.4 km^3 for the Heiheiahulu shield. The average dormant interval has been about 13.6 years during the past 1500 years. The most recent eruption occurred in 1961, and the area may be overdue for its next eruption. However, eruptive activity will not resume on the LERZ until either the dike feeding the current eruption on the middle east rift zone extends farther down rift, or a new dike, unrelated to the current eruption, extends into the LERZ.

Introduction

Kilauea is an active tholeiitic shield volcano in the southeastern part of the Island of Hawaii (Fig. 1). Its east rift zone, a site of intense flank eruptive activity during Quaternary time, is about 125 km long, including the 70-km-long submarine Puna Ridge (Fornari 1987). The lower segment (LERZ) of the subaerial east rift zone forms the easternmost part of the island. The LERZ was chosen for study because of its frequent eruptions, burgeoning population, potential volcanic hazards, relatively good access, and current exploration for geothermal energy.

This report summarizes the results of detailed 1:24000-scale field geologic mapping (Moore and Trusdell 1991) of the LERZ and adjoining flanks of Kilauea. I describe the volcanic hazards in the area, partly because commercial and residential development on and near the LERZ continues almost unabated, with little recognition by developers and government authorities that Kilauea is one of the world's most active volcanoes.

Lava flows erupted from vents in the LERZ form the adjoining northern and southern flanks of Kilauea and underlie most of the area of this report (Fig. 2). Pahoehoe flows erupted from the Ai-laau vent on the eastern summit of Kilauea (Holcomb 1987) cover the northwestern part of the map area. Lava flows from the 1983–1991 eruption of Kilauea have reached as close as about 1 km west and 700 m south of the study area (Hawaiian Volcano Observatory, unpublished data).

The area of this report receives more than 100 in (250 cm) of rainfall annually and was covered by tropical rain forest, now widely cleared for agriculture and houses. Vegetation begins to grow on lava a few months after its eruption. Relative heights of trees can be a guide to relative ages of underlying rocks, but proximity to faults, presence of easily weathered cinders, flow morphology (aa or pahoehoe), and human activity also affect the rate of growth.

Stearns and Macdonald (1946) presented a generalized geologic map of Kilauea, showing locations of historic flows and many prehistoric vent deposits. Holcomb (1987) published photogeologic maps of Kilauea and discussed its geologic history based mainly on paleomagnetic secular-variation studies. A few of Holcomb's (1987) age assignments differ from those presented here, chiefly along the coast, where he believes that more flows are > 1500 years old. Wright and Fiske (1971) discussed the petrology of some LERZ lavas. Moore (1983) related the distribution of vents for differentiated tholeiites on the LERZ to possible secondary magma reservoirs, whose associated hydrothermal

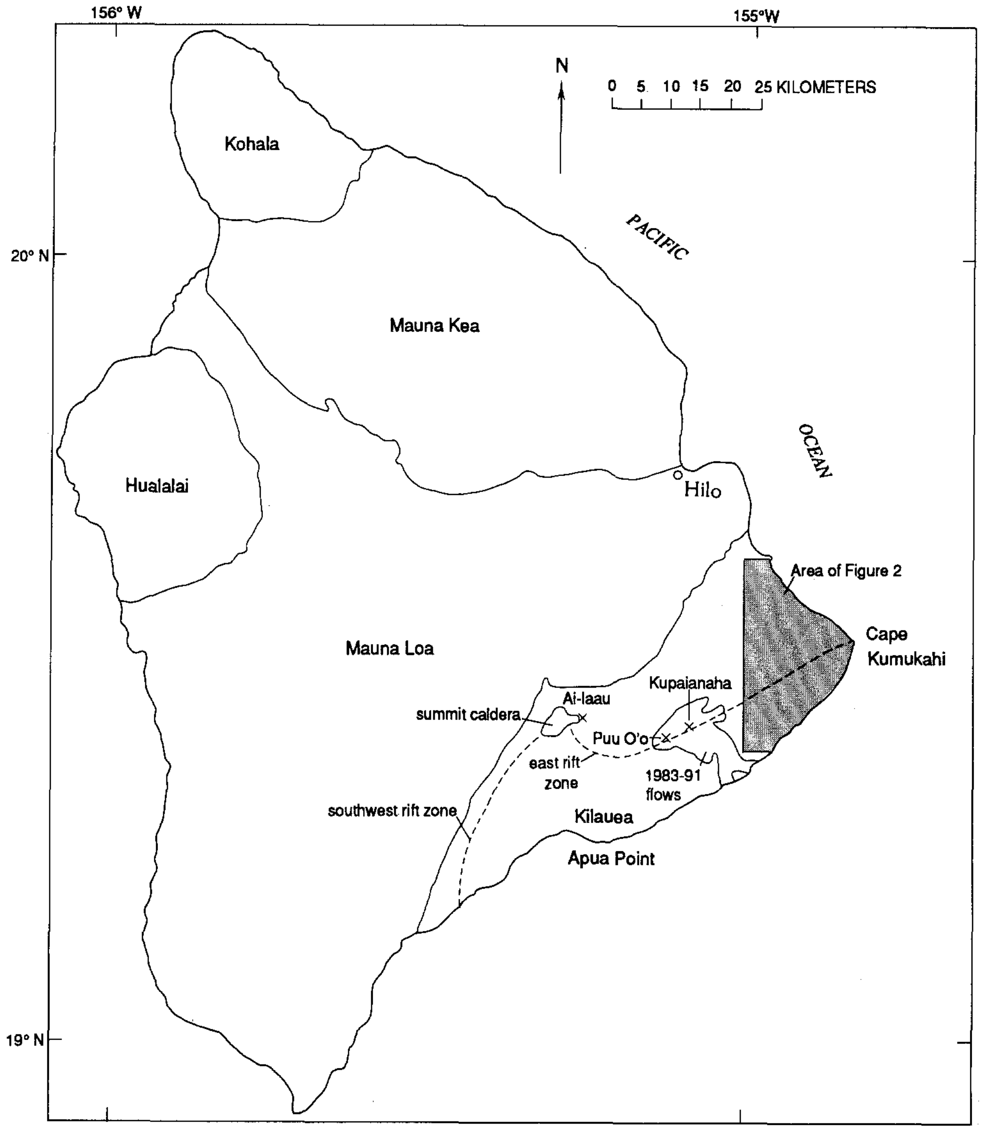

Fig. 1. Index map of the Island of Hawaii and its five volcanoes. The area of this report, the active Kupaianaha shield, and Kilauea's 1983–1991 lava flows, are shown

systems might be potential targets for geothermal exploration.

Vent deposits and lava flows in the study area consist of olivine-controlled, differentiated, and hybrid tholeiitic basalt (Wright and Fiske 1971; Ho and Garcia 1988). Phenocrysts include olivine, plagioclase, sparse clinopyroxene, and rare orthopyroxene; some rocks are aphyric. Picritic tholeiite was extruded during at least nine eruptions. Inclusions of gabbro and olivine gabbro as large as 10 cm across are abundant in some rocks and present as small (1 cm) clots in about half of the spatter deposits and flows. Inclusions of dunite and pyroxenite, which may simply be aggregates of phenocrysts, are less common.

Structure

The subaerial LERZ strikes N 65° E and is 3–4 km wide and about 23 km long. It is a constructional ridge, 50–150 m above the adjoining terrain, marked by low spatter ramparts and cones as high as 60 m. Its elevation gently decreases from southwest to northeast and ranges from a high of 522 m above sea level at Heiheiahulu to sea level at Cape Kumukahi (Fig. 2). Lava typically flowed either northeast or southeast, depending on vent location relative to the topographic crest of the rift zone.

The northern flank of Kilauea adjoining the LERZ is buttressed by Mauna Loa volcano (Fig. 1), whereas the southern flank is unbuttressed and free to slide gravitationally southward. Normal faulting that results from intrusion of magma into the east rift zone thus has resulted in a steeper topographic profile on the southern side (Swanson et al. 1976). Faults having cumulative displacements of as much as 15 m have the same N 65° E trend as eruptive fissures and cut vent deposits and flows in and near the rift zone (Fig. 3). Narrow grabens often form near eruptive sites. Intrusion without eruption of magma in 1924 caused graben subsidence of 3–4 m in the village of Kapoho (Stearns and Macdonald 1946).

Vents for single eruptions typically occur discontinuously along lengthy (as much as 30 km) segments of

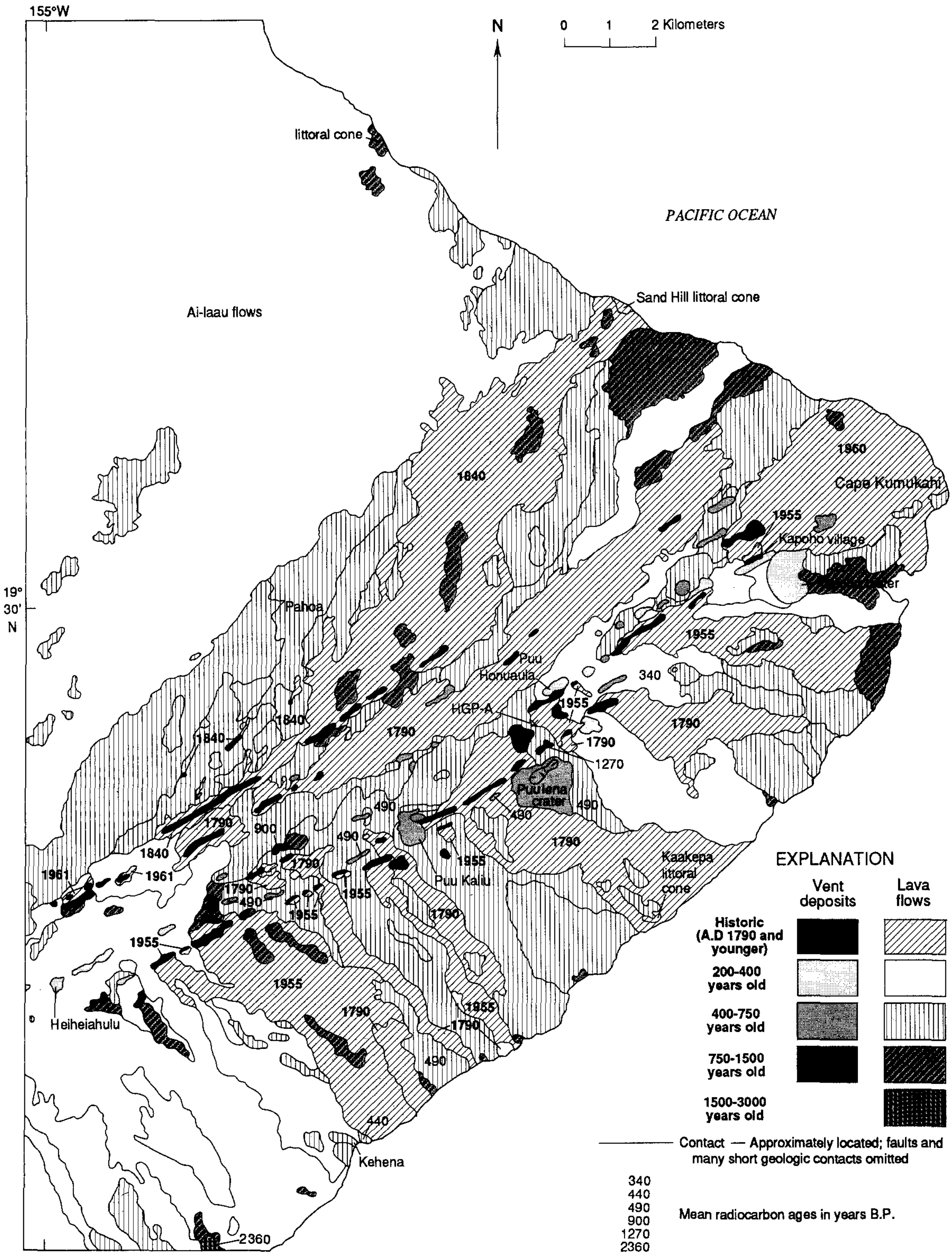

Fig.2. Generalized geologic map of the lower east rift zone of Kilauea volcano. (Major faults are shown on Fig. 3)

the east rift zone. Eruptive vents on the northern side of the LERZ commonly are en echelon and left-stepping. Eruptive vents on the southern side of the LERZ commonly are en echelon and right-stepping in its western part eastward to the vicinity of Puulena Crater (Fig. 2); the vents then shift left (northward) and are left-stepping farther east, down the LERZ. Individual steps typically are 10–100 m north or south. Some small vents, such as those associated with the 1840 and Puu Honuaula eruptions (Figs. 2 and 4), are located several hundred meters north of the principal fissure system. During the 1979 eruption on Kilauea's upper east rift zone, a small vent also formed in an anomalous position north of the main eruptive fissure (Banks et al. 1981).

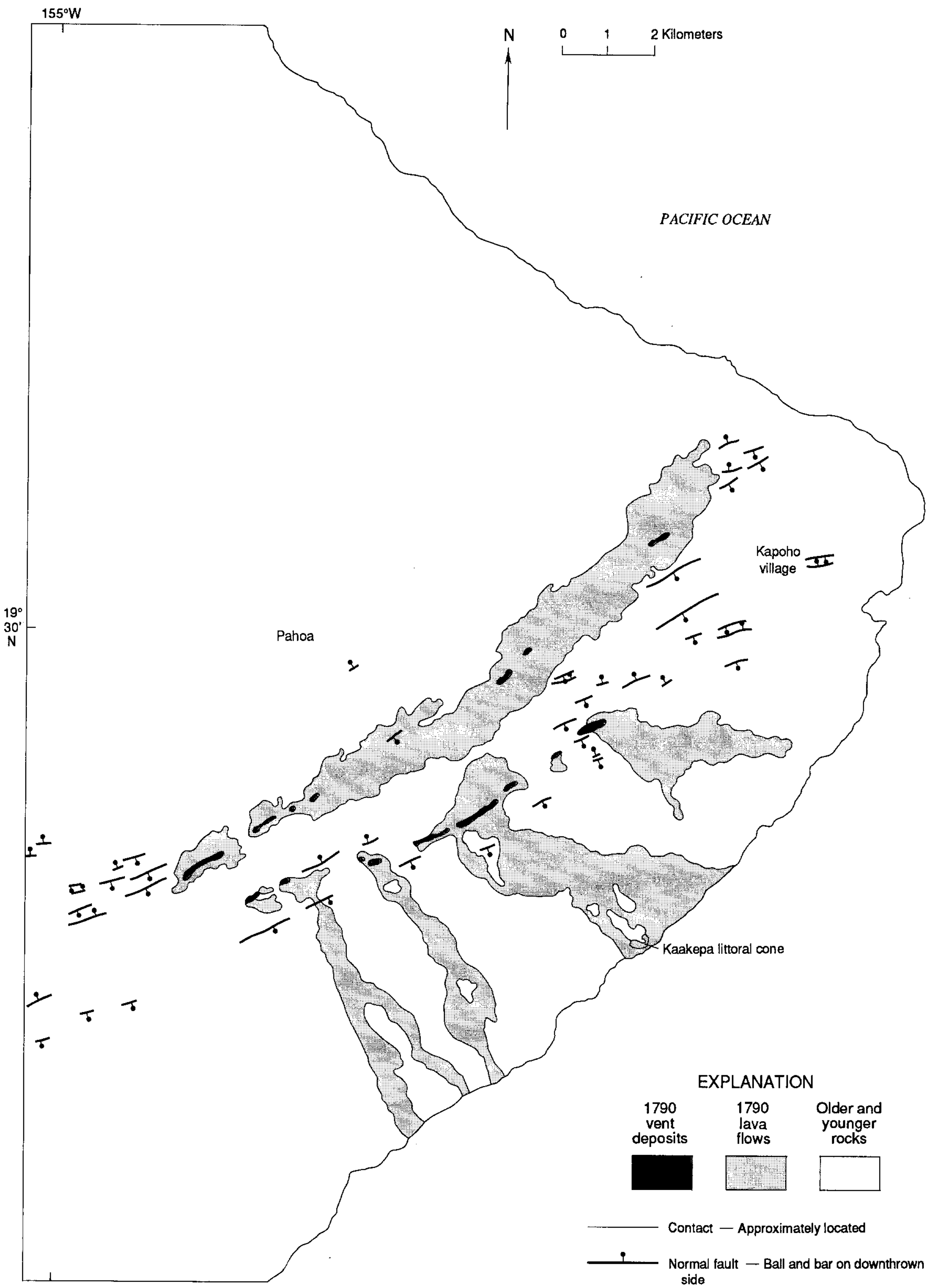

Fig. 3. Map showing the distribution of vent deposits and lava flows erupted around AD 1790. Major faults in the study area (Moore and Trusdell 1991) are shown

The northward shift of long eruptive fissures, a northwest-trending electrical self-potential anomaly, and microearthquake epicenters aligned along a northwest trend near Puulena Crater led Zablocki and Koyanagi (1979) to suggest that a transform fault striking approximately perpendicular to the rift zone might underlie this area. However, all surface faults and eruptive fissures near Puulena Crater strike N 65° E and none correspond to the structure inferred from geophysical studies. The cause of the northward shift of eruptive

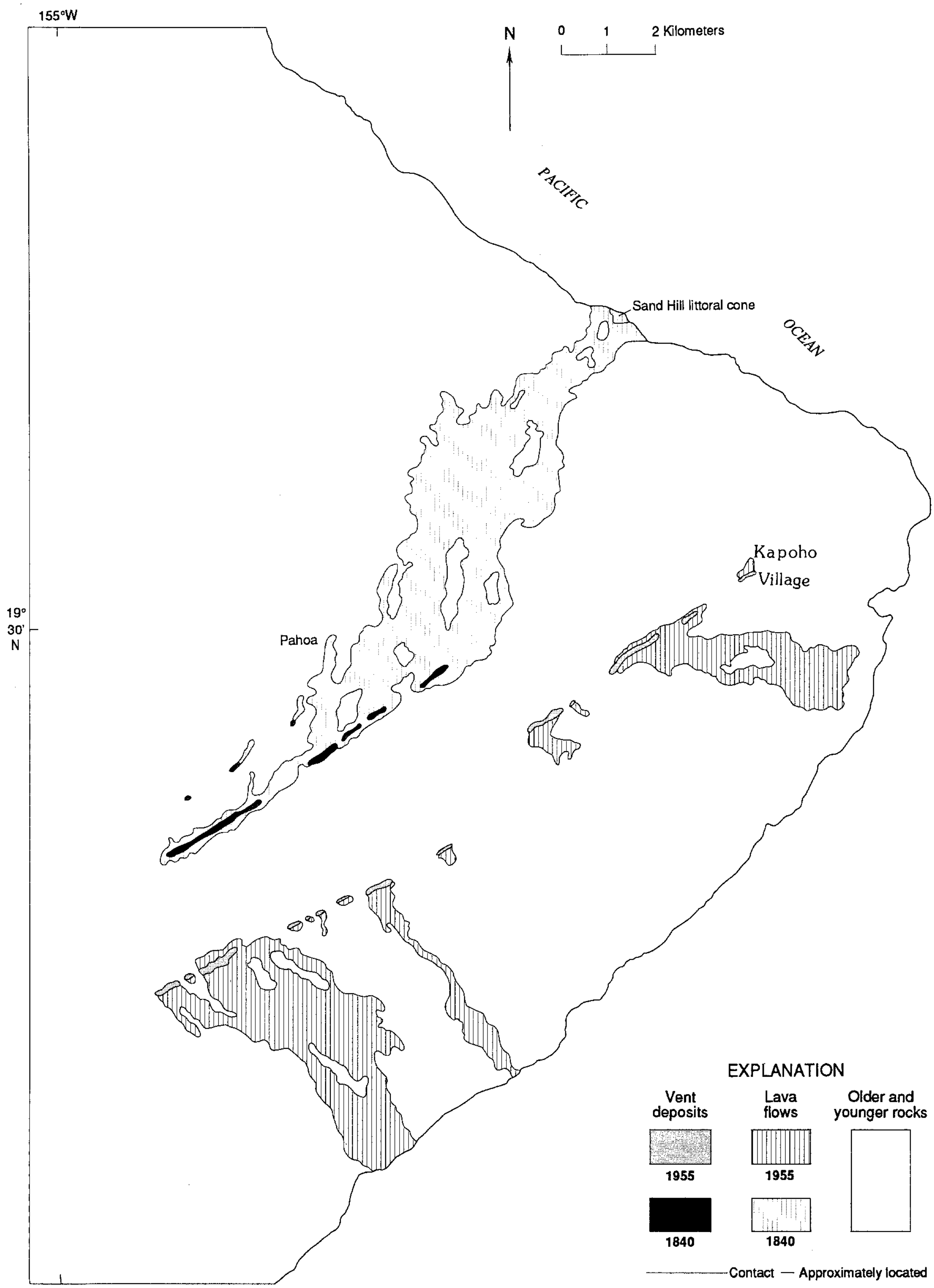

Fig. 4. Map showing the distribution of vent deposits and lava flows erupted in AD 1840 (this report) and 1955 (after Macdonald and Eaton 1964)

fissures near Puulena Crater is not known but may be related to greater displacement of the southern flank of Kilauea in the western part of the study area compared to the eastern part. More voluminous and frequent magmatic intrusions higher on the east rift zone may result in differential stress within the adjacent southern flank, leading to selective failure of blocks bounded by now-buried faults perpendicular to the axis of the rift zone (Zablocki and Koyanagi 1979).

Stratigraphy

Rocks of five Holocene age groups (Wolfe and Morris 1989) are present in the study area. The framework for the ages assigned is provided by eight radiocarbon dates on charcoal recovered from beneath flows and spatter. The numerical ages are supplemented by observations of stratigraphic relations, degree of weathering, soil development, and vegetative cover. Differences in phenocryst types and abundances facilitate mapping of vent deposits and flows of separate eruptions.

LERZ vent deposits include low (2–10 m) spatter ramparts, spatter cones as high as 60 m, two extensive lithic-rich tuff deposits, local cinder-fall deposits, and the Heiheiahulu shield. Flows are pahoehoe or aa and typically extend 2–6 km from their vents; their range is a few tens of meters to more than 9 km. In contrast, flows from Ai-laau at the eastern summit of Kilauea extend as much as 40 km from their vent. Flows in the study area range in thickness from 1–8 m at their margins to as much as 20 m where their central parts are exposed in sea cliffs. Three littoral cones, two of historic age, were built where lava flowed into the ocean.

Rocks 1500–3000 years old

A single small pahoehoe flow comprises this map unit (Fig. 2). The flow extends south of the study area, where it overlies a littoral cone in an artificial excavation at the Kalapana-Kaimu dump. The radiocarbon age of the flow is 2360±90 years BP. Since this eruption is the only one known during this time period (the next oldest radiocarbon-dated eruption occurred 1270±70 years BP), the average dormant interval in the study area from 1500–3000 years BP is unknown. Many more eruptions, whose products are buried by younger rocks, probably occurred during this period.

Rocks 750–1500 years old

The products of 37 known eruptions during this time interval cover about 5% of the map area (Fig. 2). Rocks include spatter deposits formed during 17 separate eruptions, 11 lava flows associated with those spatter deposits, and 20 lava flows whose associated vents are buried by younger rocks. Most exposures are limited in areal extent (<1 km^2), but three flows underlie several km^2 in the eastern part of the study area. The volume of lava erupted during this time interval is poorly known, owing to burial by younger lava. Radiocarbon ages of two spatter cones are 1270±70 and 900±70 years BP. The average dormant interval (based on the known eruptions) during this time period was about 20.8 years. Many more eruptions, whose products are buried by younger rocks, probably occurred.

Rocks 400–750 years old

The products of 54 known eruptions during this time interval cover about 20% of the study area (Fig. 2). Rocks include spatter deposits formed during 26 separate eruptions, 18 lava flows associated with those spatter deposits, 27 lava flows whose associated vents are buried by younger rocks, and one tuff deposit. Individual flows underlie areas as large as 11 km^2. The volume of lava erupted during this time interval is poorly known, owing to burial by younger lava.

One voluminous eruption during this time interval formed the spatter cone of Puu Kaliu (Fig. 2), associated small spatter ramparts, and thick aa flows. The right-stepping eruptive fissure extends about 1.5 km along the southern side of the LERZ. Aa flows, commonly 15 m or more thick, covered at least 12 km^2. The estimated volume of the Puu Kaliu eruption is about 0.2 km^3.

Overlying Puu Kaliu and its flows are low spatter ramparts and aa and pahoehoe flows of another large eruption that occurred 490±60 years BP. Spatter ramparts formed along a discontinuous, right-stepping eruptive fissure about 6.5 km long on the southern side of the LERZ (labeled 490 on Fig. 2). Lava flows covered at least 18 km^2 and have a volume of nearly 0.2 km^2.

Another large eruption occurred 440±60 years BP. Exposures are poor, owing to burial by Heiheiahulu and 1955 lava. A 20-m-high sea cliff near Kehena (Fig. 2) includes 15 separate flow units that may be associated with a now-buried shield similar to Heiheiahulu. The volume of this eruption is unknown but probably exceeds 0.1 km^3.

An unusual eruption during this time interval resulted in deposition of unconsolidated, unstratified, lithic-rich tuff near Puulena Crater in the central LERZ (Fig. 2). Discontinuous exposures of tuff extend across more than 4 km^2, overlie a spatter cone dated at 1270±70 years BP, and underlie the lava flow dated at 490±60 years BP. Tuff as thick as 20 m was deposited during violent phreatic eruptions that probably resulted when ascending magma encountered perched groundwater or a hydrothermal reservoir. Collapse near the end of the phreatic explosions formed the three largest pit craters, including Puulena Crater, on the LERZ.

The average dormant interval, based on the known eruptions, during this time period was about 6.6 years. Several more eruptions, whose products are buried by younger rocks, may have occurred.

Rocks 200–400 years old

The 15 map units of this time interval cover about 50% of the study area. Spatter deposits and lava flows of ten separate eruptions, four lava flows whose associated vent deposits are either buried by younger rocks or outside the study area, and one tuff cone are included. Flows from Heiheiahulu cover at least 45 km^2. Flows from the Ai-laau vent (Holcomb 1987) at the eastern summit of Kilauea cover about 100 km^2 in the northwestern part of the study area. Excluding Ai-laau flows, the volume of lava extruded on the LERZ during this time interval is at least 1 km^3.

Kapoho Crater (Fig. 2), about 1.2×0.9 km across and 118 m high, is a prominent tuff cone in the eastern part of the LERZ. Tuff from Kapoho Crater may have originally covered an area of at least 6 km^2, although most of the weakly consolidated deposit has been removed for agriculture, and its distribution is poorly known. Exposures in roadcuts on the cone include locally cross-bedded lithic-rich surge deposits. The base of Kapoho Crater is only 20 m above sea level; violent phreatic explosions resulting from the interaction of ascending magma and seawater produced the tuff. Tuff from Kapoho Crater mantles flows as young as those from Puu Honuaula and is overlain by flows from three separate eruptions that occurred <340–>200 years BP.

Heiheiahulu (Fig. 2) is the only lava shield on the present surface of the LERZ. Early episodes of the eruption formed spatter ramparts along a 3.5-km-long segment of the southwestern LERZ and extruded extensive aa flows. Eruptive activity eventually became centralized at Heiheiahulu, where pahoehoe flows built a shield and covered a large area on the southern flank of Kilauea. Collapse of the vent area near the end of the eruption formed a pit crater whose walls include some of the early spatter deposits. By analogy with the Mauna Ulu shield (Swanson et al. 1979; Tilling et al. 1987) and the current Kilauea activity at the Kupaianaha shield (Fig. 1), eruptions at Heiheiahulu may have continued for several years.

Few dates are available for this age group. The radiocarbon age of the flow from Puu Honuaula is 340 ± 60 years BP. Oral Hawaiian legends suggest that the Heiheiahulu shield formed during the first half of the eighteenth century (Stearns and Macdonald 1946). The average dormant interval, based on the known eruptions, during this time period was about 14.3 years. Additional eruptions, whose products are buried by rocks of historic age, may have occurred.

Rocks of historic age (AD 1790 and younger)

Vent deposits, lava flows, and littoral cones of historic age cover about 25% of the study area. Eruptions occurred in 1790, 1840, 1955, 1960, and 1961 and extruded a total of at least 0.6 km^3 of lava.

Voluminous eruptions around 1790 (Fig. 3), including at least 0.2 km^3 in the study area alone, may have contributed to caldera collapse at the summit of Kilauea (Holcomb 1987). Magma withdrawn from the reservoir underlying the summit area and intruded as dikes down virtually the entire length of the subaerial east rift zone may have resulted in an unsupported upper volcanic edifice. Two separate dikes (Fig. 3) were intruded in the LERZ; the eruptive fissures are 1 km apart at their uprift (southwestern) end but gradually diverge to about 2 km apart at their downrift (northeastern) end. The southern fissure system, about 8.5 km long, shows right-stepping en echelon displacement of individual vents for its western 6 km; the eruptive vents then shift left (northward) and are left-stepping for the last 2.5 km downrift. The northern 1790 eruptive fissure is mostly left-stepping throughout its 13 km length. Flows from the two eruptive fissures are not in contact, and their relative ages cannot be determined. Flows of 1790 cover about 35 km^2. A small littoral cone (Kaakepa; Fig. 3) was built where 1790 aa flowed into the ocean. Radiocarbon ages of one flow from each fissure system are <200 years BP.

The 1840 eruption (Macdonald 1944) extruded a small volume of aphyric tholeiite in the upper east rift zone and about 0.15 km^3 of picritic tholeiite that covered about 20 km^2 of the study area. Most vents on the LERZ occur along a 7.5-km-long segment in its northern part. In addition, five small vents erupted along a 2.8-km-long fissure 0.9 km north of and parallel to the main 1840 vents (Fig. 4). Aa from the main vents flowed to the ocean, where steam explosions built a littoral cone, Sand Hill.

The 1955 eruption (Macdonald and Eaton 1964) lasted 88 days, during which about 0.11 km^3 of lava covered about 16 km^2 and destroyed 21 houses. Vents formed discontinuously along a 15.8-km-long segment of the southern LERZ. Similar to the southern eruption of 1790, most western vents are right-stepping for 7.5 km down the LERZ; the fissure system, after a non-eruptive gap 2.5 km long, steps left 1.2 km and is left-stepping another 5.8 km to its terminus in Kapoho village (Fig. 4).

The 1960 eruption (Richter et al. 1970) occurred along a 1-km-long fissure system near Kapoho (Fig. 2). It followed, after a hiatus of 25 days, the November-December 1959 eruption at Kilauea Iki on the volcano's eastern summit. Prior to the onset of the eruption, earthquake epicenters migrated at least 5 km down the LERZ to the vicinity of Kapoho. Four days after the eruption began, Kilauea's summit began to subside as magma was withdrawn from the summit reservoir. The eruption lasted 38 days and extruded about 0.125 km^3 of lava that covered 10 km^2 and destroyed the villages of Kapoho and Koae, a US Coast Guard station, and several other residences (Richter et al. 1970).

The one-day 1961 eruption (Richter et al. 1964) extruded only about 250000 m^3 of lava that covered less than 1 km^2 of uninhabited rain forest in the western part of the LERZ (Fig. 2). Eruptive vents generally are left-stepping, characteristic of others on the northern side of the LERZ.

The average dormant interval from 1790–1961 was 42.75 years, much longer than during the period from 1500–200 years BP. Historic repose periods have varied considerably, however. No eruptions occurred in the study area between those of 1840 and 1955, and three (1955, 1960, and 1961) occurred during a seven-year period.

Past and future volcanic hazards on the LERZ

Most eruptions on and near the LERZ have been non-explosive and pose little danger to human beings. The chief threat is to buildings, roads, and other man-made structures. Many residential subdivisions have been developed in the study area during the past 40 years, partly because of the lack of eruptive activity from 1840–1955 (Holcomb 1987). Lava flows of the 1983–1991 eruption from vents in the middle east rift zone destroyed 180 houses on the southern flank of Kilauea, and a similar or greater number could be affected by future eruptions in densely populated parts of the study area.

Spatter and cinder deposits cause relatively little damage, unless a structure is near an active vent. Lava flows in the study area caused considerable damage to structures in 1955 and 1960. While it is feasible to divert lava away from threatened structures in certain circumstances (Richter et al. 1970; Lockwood and Torgerson 1980; Lockwood 1988), a natural or artificial barrier can be overwhelmed during a sustained eruption. In populated areas, additional legal and political difficulties are associated with the protection of one piece of property at the expense of another.

The products of two major explosive eruptions have been recognized on the LERZ. Puulena tuff, which was deposited between 1270 and 490 years BP, devastated an area of at least 4 km^2. Kapoho Crater, which is younger than 340 years BP, erupted pyroclastic surges that devastated at least 6 km^2. Explosive eruptions similar to those at Puulena and Kapoho Craters are potentially life-threatening and may be difficult to predict. Careful monitoring of future seismic, intrusive, and eruptive activity near Puulena Crater and between Kapoho Crater and the ocean will help mitigate the hazards associated with these infrequent but dangerous explosive eruptions. Immediate evacuation after the onset of phreatic or phreatomagmatic explosions may be the safest procedure.

A different kind of explosive activity forms littoral cones where lava flows into the ocean. These explosions affect relatively small areas, however, and the formation of the three littoral cones found in the study area would not have presented a hazard beyond the immediate area where lava was entering the ocean.

Hazards associated with geothermal investigations

Current exploration for geothermal energy on the LERZ is a controversial subject. Data presented in this paper suggest that development of potential geothermal resources may be affected by future volcanic eruptions.

The State of Hawaii supported drilling of a geothermal well, HGP-A, into the area of the self-potential anomaly about 1 km north of Puulena Crater (Fig. 2). HGP-A has a maximum temperature of 358° C (Thomas 1985). Private companies have drilled several additional wells, mainly near HGP-A. Temperatures of the private wells are nearly as hot as HGP-A, but most information is proprietary (Thomas 1985). Little is known about the amount of steam available or the configuration of potential reservoirs. Assessment of the potential geothermal resource in the area of this report by the US Geological Survey, the State of Hawaii, and private companies is continuing.

Summary and discussion

At least 111 separate eruptions from vents on the LERZ have extruded an estimated 4.5–6 km^3 of tholeiitic basalt during the past 1500 years.

The length of the average dormant interval between eruptions increased from about 12.4 years or less during 1500–200 years BP to 42.75 years from 1790–1961, indicating that the eruption rate on the LERZ is not constant. During historic time, eruptions on the LERZ have been infrequent during periods of relatively frequent summit activity (Holcomb 1987). Kilauea may have behaved in a similar manner in the past; there may have been no eruptions on the LERZ for decades, followed by periods of relatively frequent activity. For example, the large area south of the east rift zone, extending from Apua Point to Cape Kumukahi (Fig. 1), had no eruptions for 165 years. However, since 1955 about 30% of that area has been covered by lava, most recently from the continuing Puu O'o/Kupaianaha eruption that began in 1983.

The average dormant interval on the LERZ has been about 13.6 years during the past 1500 years. Thirty years have elapsed since the most recent LERZ eruption in 1961, and the area may be overdue for its next eruption.

In any small area on the LERZ and adjoining flanks of Kilauea, the average dormant interval is usually much longer than the intervals reported above for the entire study area. For example, 165 years elapsed between burial of adjacent areas during the eruptions of 1790 (southern fissure and flows) and 1955. However, houses were destroyed in Kapoho village in 1955 and 1960. Kapoho may be particularly vulnerable, since five other eruptions (Fig. 2) occurred in its vicinity 340–>200 years BP.

Average dormant intervals during the past 1500 years are not completely accurate guides to the date and location of future eruptive activity, but they can serve as a basis for assessing the potential volcanic risk as the human population increases on and near the LERZ. The risk of burial by lava is high, and government planners should work closely with commercial and residential developers to minimize the potential loss of valuable property, including existing or planned houses, commercial buildings, farms, golf courses, geothermal wells, and electrical power plants.

The current eruption at the Kupaianaha shield about 9 km west of Heiheiahulu may be part of a Kilauea cycle, suggested by Holcomb (1987), in which long periods of summit-dominated eruptions alternate with long periods of east rift activity. Since 1955, Kilauea has entered a period of intense east rift activity. This fact and the data of this paper suggest some possibilities for future activity that might follow the end of eruptions at Kupaianaha: (1) the dike feeding Kupaianaha may migrate farther down the east rift zone and eruptions could affect the LERZ; (2) the current eruptive site may be cut off from the supply of magma and eruptions could break out higher on the east rift zone or at Kilauea's summit; or (3) after the Kupaianaha eruption ends, a new dike could be emplaced in the east rift zone and possibly extend into the LERZ.

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