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Zinzuni Jurado-Chichay · Scott K. Rowland
George P. L. Walker

The formation of circular littoral cones from tube-fed pāhoehoe: Mauna Loa, Hawai'i

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Abstract Pyroclastic cones along the southwest coast of Mauna Loa volcano, Hawai'i, have a common structure: (a) an early formed circular outer rim 200–400 m in diameter composed mostly of scoria and lapilli, and (b) one or more later-formed inner rims composed almost exclusively of dense spatter. The spatter activity locally fed short lava flows that ponded within the outer rims. Based on various lines of evidence, these cones are littoral in origin: relationships between the cones and associated flows; the degassed nature of the pyroclasts; and (although not unequivocal) the position of the cones relative to known eruptive vent locations on Mauna Loa. Additional support for the littoral interpretation comes from their similarity to (smaller) littoral cones that have been observed forming during the ongoing Kīlauea eruption. The structure of these Mauna Loa cones, however, contrasts with that of "standard" Hawaiian littoral cones in that there is (or once was) a complete circle of pyroclastic deposits. Furthermore, they are large even though associated with tube-fed pāhoehoe flows instead of 'a'ā. The following origin is proposed: An initial flow of tube-fed pāhoehoe into the ocean built a lava delta with a base of hyaloclastite. Collapse of an inland portion of the active tube into the underlying wet hyaloclastites or a water-filled void allowed sufficient mixing of water and liquid lava to generate strong explosions. These explosions broke through the top of the flow and built up the outer scoria/lapilli rims on the solid carapace of the lava delta. Eventually, the supply of water diminished, the explosions declined in intensity to spattering, and the initial rim was filled with spatter and lava.

Key words Littoral cones · Mauna Loa · Volumetric flow rate · Lava tubes · Lava–water interaction · Lava delta · Bench collapse

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Zinzuni Jurado-Chichay (✉) · George P. L.Walker
Hawai'i Center for Volcanology and Department of Geology and Geophysics, University of Hawai'i at Mānoa,
2525 Correa Road, Honolulu, Hawai'i 96822, USA

Scott K. Rowland
Hawai'i Center for Volcanology and Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa,
2525 Correa Road, Honolulu, Hawai'i 96822, USA

Introduction

Littoral cones develop around secondary or rootless vents as a result of steam explosions that take place when lava flows into the ocean (e.g., Moore and Ault 1965; Macdonald 1972; Fisher and Schmincke 1984). Similar secondary cones from the interaction of lava and water (or wet sediments) can also be found in Iceland (Morrissey and Thordarson 1991; Thordarson and Self 1993), and on Volcán Cerro Azul in the Galápagos (e.g., Munro 1992; Jurado-Chichay et al. 1993).

On the island of Hawai'i there are about 50 littoral cones along the coastlines of Mauna Loa and Kīlauea volcanoes (Moore and Ault 1965). Three of the largest formed during the 1840 eruption of Kīlauea (Brigham 1909) and the 1868 and 1919 eruptions of Mauna Loa (Brigham 1909; Jaggar 1919; Fisher 1968), all of which were associated with channelized high-discharge-rate flows. Small littoral cones and deposits also formed during the tube-fed pāhoehoe eruptions of Mauna Ulu and Pu'u 'Ō'ō/Kūpa'ianahā (Kīlauea) in 1969–1974 and 1986–1995, respectively (e.g., Moore et al. 1973; Peterson 1976; Heliker and Wright 1991; Thordarson and Self 1991; Sansone and Resing 1991a, b; Mattox 1993, 1994). These cones were rarely >10 m high, and developed on the lava bench just inland from the point where lava entered the ocean.

When a flow enters the ocean the water is rapidly converted to steam, which expands either passively or explosively depending on the rate of heat transfer and the degree of confinement of the mixing. Explosive vaporization fragments the lava, leading to the accumulation of pyroclastic debris. In most cases explosions are small and the pyroclastic cones that develop are also small. The most often cited form of a Hawaiian littoral deposit is two half cones approximately equal in size on either side of the parent lava flow (e.g., Fisher 1968; Fisher and Schmincke 1984); any pyroclastics that land on the moving part of the flow are carried away. Additionally, littoral cones are usually considered to be associated with ʻaʻā lava flows (Macdonald 1972; Macdonald et al. 1983). Fisher and Schmincke (1984) noted that circular littoral cones could also form over lava tubes and Mattox (1994) presents a recent example of this process on Kīlauea. This paper describes and proposes a formation scenario for a number of large circular littoral cones that are related to tube-fed pāhoehoe.

The field area

The field area consists of the southwest coastline of the island of Hawaiʻi (Fig. 1) from near Ka Lae (South Point) to the northernmost 1950 Mauna Loa lava flow. In much of the southern portion the land surface slopes

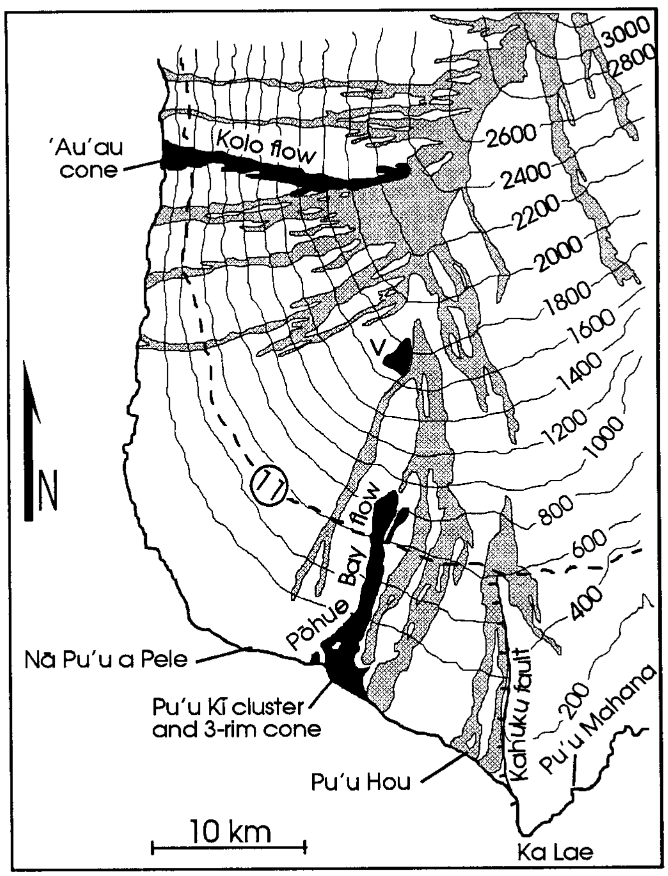

Fig. 1 Location map of southwestern Mauna Loa, showing the Kolo and Pōhue Bay flows (*black*), historical flows (*cross-hatched*), and other features mentioned in the text. The mapped vent area (*V*) of the Pōhue Bay flow (also *black*) is at ~1800 m elevation. Traced from Lipman and Swenson (1984). Contour interval 200 m

gently to the coastline, with a near-horizontal (~1°) coastal plain up to 3 km wide. Littoral cones are common in this area, and ten clusters of them were mapped by Moore and Ault (1965), although one of these, Puʻu Mahana on the southeast coast, is a primary Surtseyan vent, rather than a littoral cone (Walker 1992). One of the largest in the area is Puʻu Hou (actually a complex of three half cones), which formed when one lobe of the 1868 flow entered the ocean (Fisher 1968). Two other lobes of the 1868 flow also entered the ocean, but did not produce significant littoral deposits. The group of cones associated with the Pōhue Bay flow (Fig. 1; Jurado et al. 1991) is distributed along about 3 km of coastline 6–9 km northwest of Puʻu Hou and consists of at least six cones in various states of erosion and burial. Seven kilometers north of the Pōhue Bay group is another prominent cluster of cones, the largest of which is Nā Puʻu a Pele. About 20 km farther up the coast the slopes of the volcano become steeper, and the coastal plain narrows to several hundred meters in width. The Kolo flow and ʻAuʻau Cone are located about 45 km north of the Pōhue Bay group (Fig. 1). Photos of the Puʻu Kī cones have been published in Cas and Wright (1988), and a photo and map of ʻAuʻau cone can be found in Stearns and Macdonald (1946).

Descriptions of the cones

The cones of the Pōhue Bay flow and the ʻAuʻau Cone of the Kolo flow generally have the same structure consisting of an outer rim of scoria and lapilli (with some spatter, scattered blocks and bombs) within which are nested one or more inner rims of dense spatter and ponded lava. Two representative structures from the Pōhue Bay flow (the "Three-rim Cone" and main Puʻu Kī cluster) and ʻAuʻau Cone to the northwest present specific relationships that help to piece together the mechanism of circular littoral cone formation.

Three-rim Cone

The olivine-phyric Pōhue Bay flow consists mostly of tube-fed pāhoehoe on the coastal plain. Lipman and Swenson (1984) mapped the vent area for the Pōhue Bay flow at about the 1800-m elevation on the SW rift zone (Fig. 1). They considered the age to be 740–910 years based on the degree of surface weathering. Recent paleomagnetic work (Jurado-Chichay et al. 1996) gives an age closer to 1300 years.

Our first example is located about 2 km southeast of Pōhue Bay (Fig. 2), and we have named it Three-rim Cone. The largest rim remnant is crescent-shaped and concave toward the ocean, about 300 m long parallel to the coast, and about 80 m wide perpendicular to the coast (Fig. 2). The highest point rises ~23 m above the surrounding area. The limbs of the crescent slope to the level of the surrounding surface at both ends (Fig. 3).

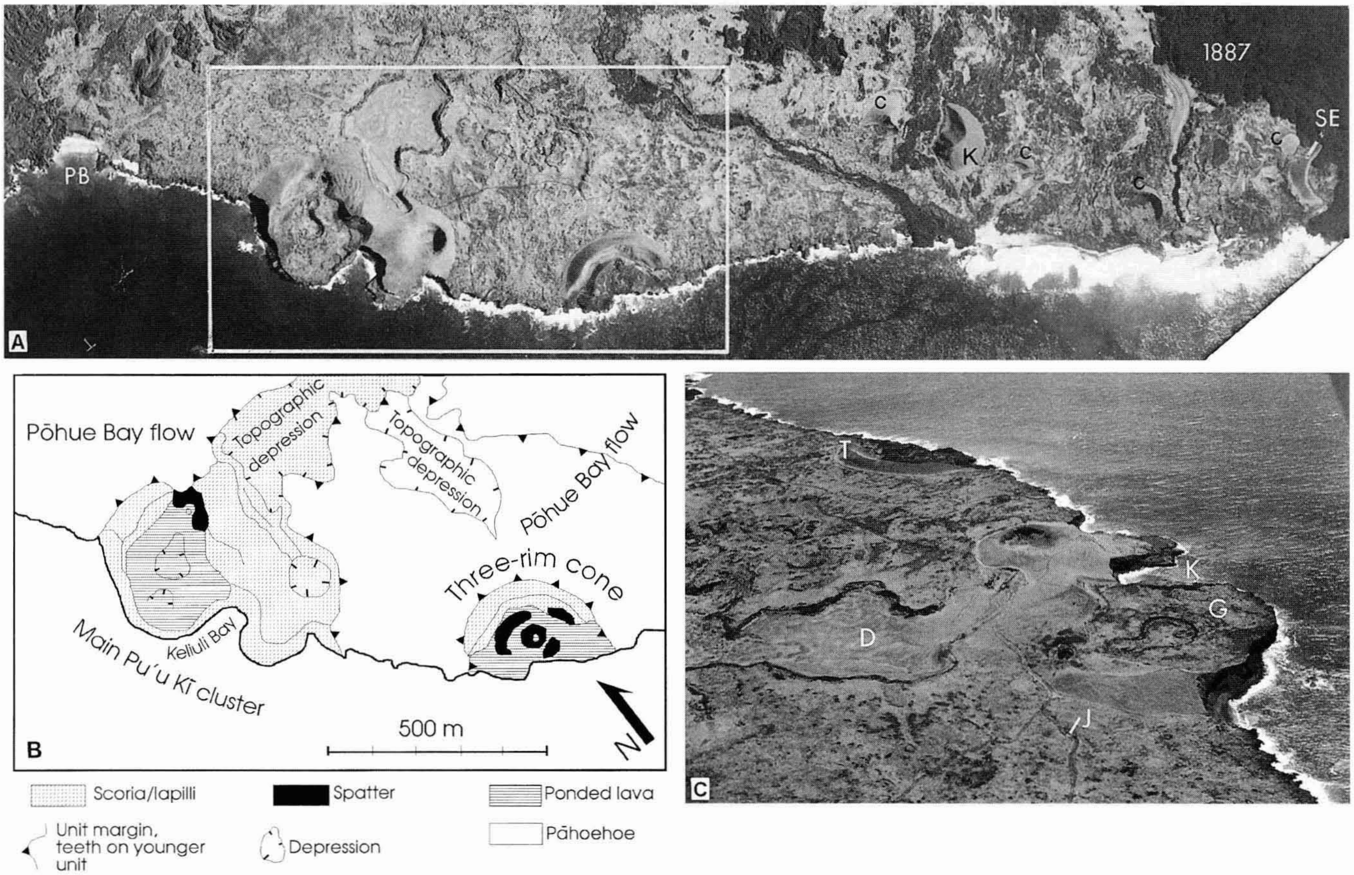

Fig. 2A–C Cones of the Pōhue Bay flow. **A** Vertical air photo (ASCS frame no. EKL 13CC 4). *PB* is Pōhue Bay. In addition to those described in the text, numerous additional littoral cones (*c*) occur associated with the Pōhue Bay flow, including Pu'u Kahakahakea (*K*; half of a typical pair of half cones) and the southeast cone (*SE*), partially buried by the *1887* lava flow. *White box* indicates area of Fig. 2b. **B** Geological map of the main Pu'u Kī cluster and the Three-rim Cone. **C** Oblique air photo (by J. P. Lockwood) looking toward the south. For orientation with respect to **A** and **B**, note the outer rim of Three-rim Cone (*T*), the topographic depression (*D*), Keliuli Bay (*K*), and the unit G lavas (*G*; see text) ponded within Pu'u Kī. Jeep road (*J*) gives an indication of scale

Pāhoehoe lava of the Pōhue Bay flow wraps around and overlies the landward side of the crescent and slopes oceanward, ending at a ~10-m-high sea cliff. The outer rim consists mostly of fine, partially palagonitized lapilli and spatter with numerous blocks and bombs up to a meter in diameter. The outer rim is poorly lithified and stratified into layers ~10–20 cm thick, and locally exposed in the ocean-facing surface of the outer rim.

The second and third (inner) rims are only a few meters high (Fig. 3) and consist entirely of large, dense spatter. They are roughly concentric to the locations of secondary spatter vents that were active late in the eruption. The two inner rims were apparently complete circular structures upon formation, but are now partially truncated by a sea cliff. Their original diameters were about 150 and 50 m. The spatter blobs of the inner rims average about 20–30 cm in size, although some are as large as 1.5 m across. A few are ribbon-like, about 10 cm wide, and up to 3 m long. The spatter is mostly confined to the inner rims, but scattered blobs and ribbons can be found on the inner slopes, crest, and outer slopes of the outer rim. Importantly (see below), a few spatter blobs can also be found outside the outer rim on the surface of the surrounding Pōhue Bay lava.

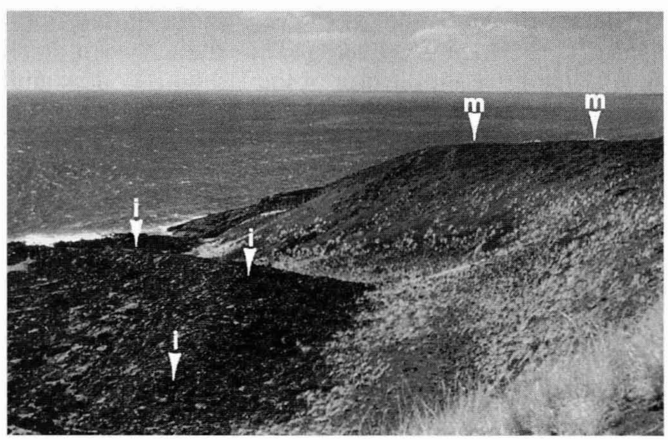

Fig. 3 The west part of Three-rim Cone. *Arrows* indicate the crests of the main outer rim and one of the inner spatter rims (*m* and *i*, respectively). Note the tonal differences between the two pyroclastic types: The fine-grained outer rim is weathered, palagonitized, and supports light-toned grasses, whereas the inner spatter is dark and essentially unweathered and unvegetated

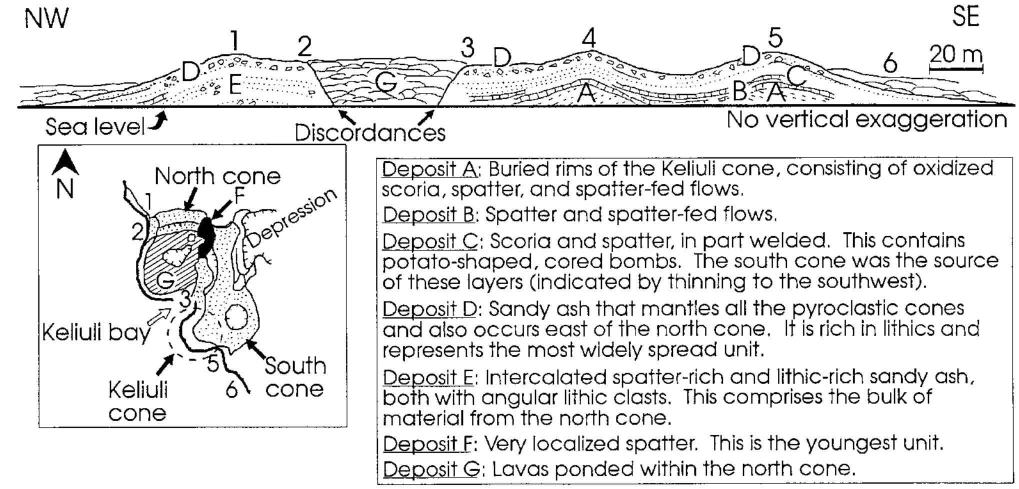

Fig. 4 Diagrammatic cross section of the main Pu'u Kī cluster as viewed from offshore. Deposits are described in *boxed list* and locations are described in text. *Inset* shows map view

In addition to the inner spatter rims, much of the area enclosed by the outer rim consists of lava that flowed from the spatter vents and accumulated in the moat between them and the outer rim. Near the center of the innermost rim is a small collapse pit. The spatter and flows from the inner rims overlie the Pōhue Bay flow at the NW and SE ends of the outer rim (Fig. 2B).

The sequence at Three-rim Cone is thus: (a) the main rim of lapilli sits on the lowermost Pōhue Bay flows and can be traced in the nearby sea cliff sloping to sea level under later Pōhue Bay flows; (b) tube-fed pāhoehoe of the Pōhue Bay flow overlaps the main rim and is banked against its entire outer perimeter to a height of up to 20 m above sea level; (c) the spatter and lava of the inner rims overlie both the main rim and the later Pōhue Bay flow.

Pu'u Kī cluster

About 300 m NW of Three-rim Cone is the main Pu'u Kī cluster. It consists of two cones and a buried remnant of a third (Figs. 2 and 4). The southernmost cone rises 20 m above the surface of the Pōhue Bay flow and has an outer diameter of ~200 m. It is circular, with a crater ~25 m deep. Numerous 1- to 2-m-thick layers of welded spatter and large, cored bombs are exposed in the walls of the crater. Lapilli-sized ejecta is relatively scarce and is found mostly near the top of the section.

The northernmost cone of the main Pu'u Kī cluster is similar to Three-rim Cone. It consists of an outer rim of mostly lapilli-, bomb-, and block-sized ejecta surrounding inner deposits of dense spatter and ponded lavas. The highest point on this outer rim is ~20 m above the surrounding Pōhue Bay flow, and the rim diameter is about 450 m. The Pu'u Kī cluster is well exposed in the ocean cliffs, and a descriptive section from NW to SE is presented in Fig. 4. At the northwesternmost exposure (location 1), the pyroclastic layers are overlain by Pōhue Bay lavas. From here the pyroclastic layers arch up and over, defining the rim and inner face of the north cone. They are truncated and unconformably overlain by flat-lying ponded lavas of unit G (location 2).

A detailed stratigraphic column of location 1 is shown in Fig. 5. The layers can generally be classified into two types, lapilli-rich and spatter-rich (both of which are olivine-rich). The lapilli-rich layers consist mostly of broken fragments of lava with numerous free, fractured olivines. One of the spatter-rich layers grades into a spatter-fed flow extending to the north, which forms the lowest unit in the low sea cliff. In addition to lapilli and spatter, all the layers contain abundant angular fragments of both vesicular and nonvesicular olivine-rich lava. Some of these fragments have densities as high as 3.4 g/cm^3. They are particularly concentrated in the uppermost layers (unit D). Generally, the lapilli-rich layers contain a higher proportion of these fragments than the spatter layers.

The next unit to the SE (G; Fig. 4) consists of flat-lying ponded lavas. These lavas are circular in plan view, mostly ~1 m thick, and have a total thickness of about 20 m. They are olivine-phyric vesicular pāhoehoe, and become more olivine-rich upward in the section. The lowermost flows rest unconformably on the inward-dipping, truncated pyroclastic layers at locations 2 and 3.

The ponded lava contains two collapse pits; the larger, seaward one is ~100 m in diameter and ~5 m deep, and the smaller, landward one is ~20 m in diameter and also ~5 m deep. Both of these pits have near-vertical striations on their walls indicating that the inner parts subsided. A low rim of dense spatter (unit F) occurs near the landward pit. It is 1–2 m high and is continuous with a thin layer of spatter that locally mantles the main cone. This spatter has the same characteristics as that which makes up the two inner rims of Three-rim Cone.

Southeast of the ponded lavas is Keliuli Bay (Fig. 6), and location 3 is essentially a mirror image of location 2. From here the pyroclastic layers arch over, then flatten out to the SE where a number of them grade into spatter-fed flows. Also exposed at Keliuli Bay is the

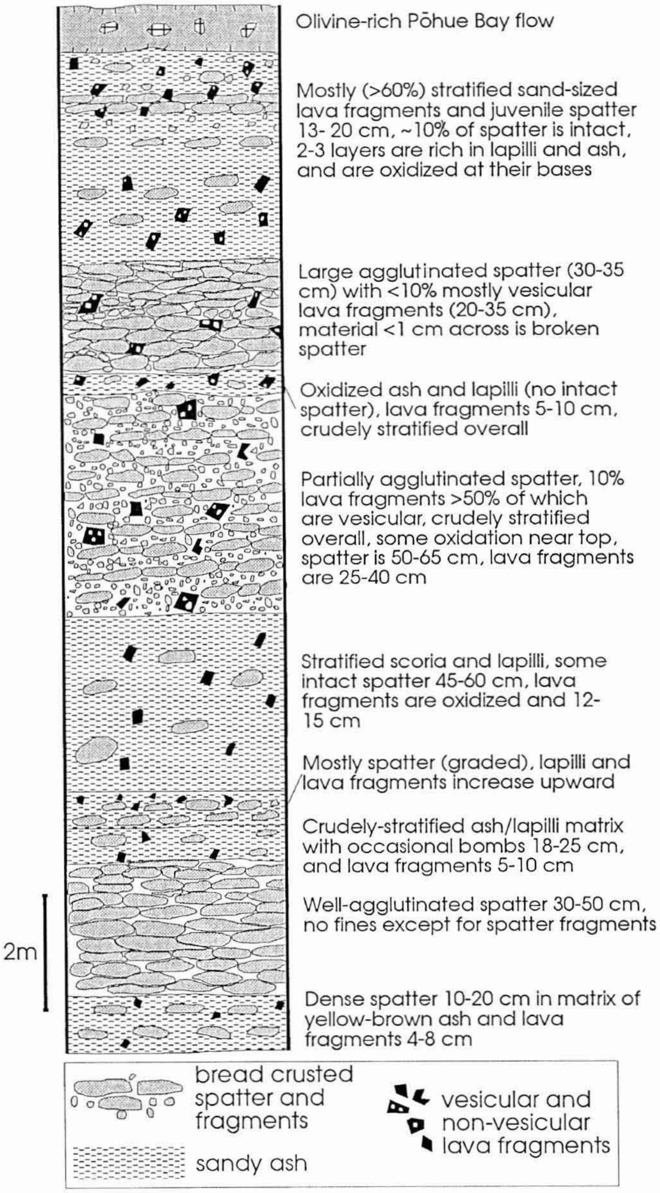

Fig. 5 Stratigraphic column of the deposits exposed at the north end of the main Pu'u Kī cluster (location 1 of Fig. 4).

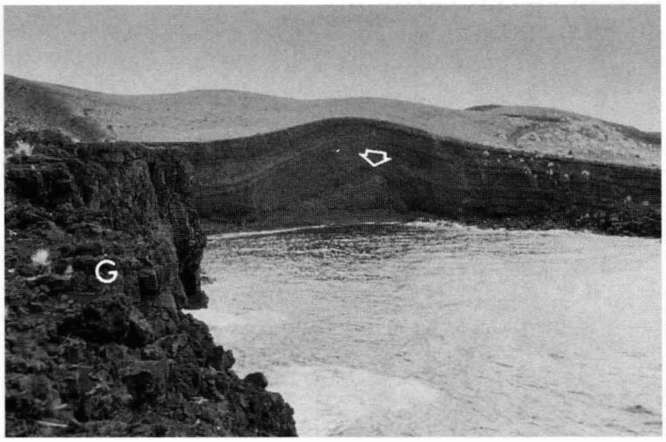

Fig. 6 A view into Keliuli Bay. *Arrow* indicates crest of NW half of the Keliuli cone (location 4 of Fig. 4). Note layers of the main north cone arching over this remnant. Differential erosion of fine- and coarse-dominated layers accentuates bedding. Dark rocks at left (*G*) are ponded lavas of unit G

NW remnant of an earlier cone. It consists of about 15 m of oxidized spatter-like pyroclastic layers dipping NW and truncated by a SE-dipping surface. This buried remnant (unit A) is termed Keliuli Cone.

The peninsula just SE of Keliuli Bay consists of welded spatter layers of Keliuli Cone that extend around to the next small indentation of the coast. In this next small bay (location 5) a thick sequence of oxidized and welded scoria (unit C) overlies the southern half of Keliuli Cone (unit A), and is in turn overlain by unit D and then Pōhue Bay lavas. The sequence of cone formation within the main Pu'u Kī group is (a) Keliuli Cone; (b) the south (complete) cone; and (c) the northernmost cone. Unit D covers much of the Pu'u Kī area including a topographic depression just inland (Fig. 2). It is consistently fine lapilli with some ash and accretionary lapilli and contains the highest number of large angular fragments. Some of these are up to 2.5 m across; fragments up to 0.5 m in size can be found more than 500 m from the center of the cone. The youngest erupted units are the ponded lavas and spatter of units F and G. Neither they nor the very latest Pōhue Bay lavas that surround the cone and topographic depression are overlain by unit D.

At location 1 the lapilli scoria tends to dominate, comprising 7 of the 10 main layers. These layers are neither welded nor oxidized; most of the scoria is dark gray. At location 5, however, dense bomb-sized scoria and ribbon-like spatter predominate, forming massive welded layers a few meters thick, most of which have been oxidized to a very bright red. Small cored bombs can be found at location 5, and each core is a nonoxidized fragment of olivine-rich basalt.

As at Three-rim Cone, the sequence consists of an early formed outer rim of pyroclasts surrounding ponded and spatter-fed lava. Although Pu'u Kī is no longer a complete cone, the ponded lavas (unit G) must have had something to pond within and a map view (Figs. 2 and 4) allows the once-complete form to be reconstructed.

A prominent depression occurs immediately inland from the main Pu'u Kī cluster (Fig. 2). This depression has an area of about 0.15 km^2 and averages 4–5 m deep. It has two branches with channel-like extensions that point in the directions of Three-rim Cone and the main Pu'u Kī cluster. It has a relatively flat floor and its walls consist mostly of slabs of pāhoehoe that have been tilted inward. In places the inner surface subsided relative to the walls and produced scrape marks in the still-plastic lava. This depression most likely is a collapsed lava rise (Walker 1991). Its possible relationship to the

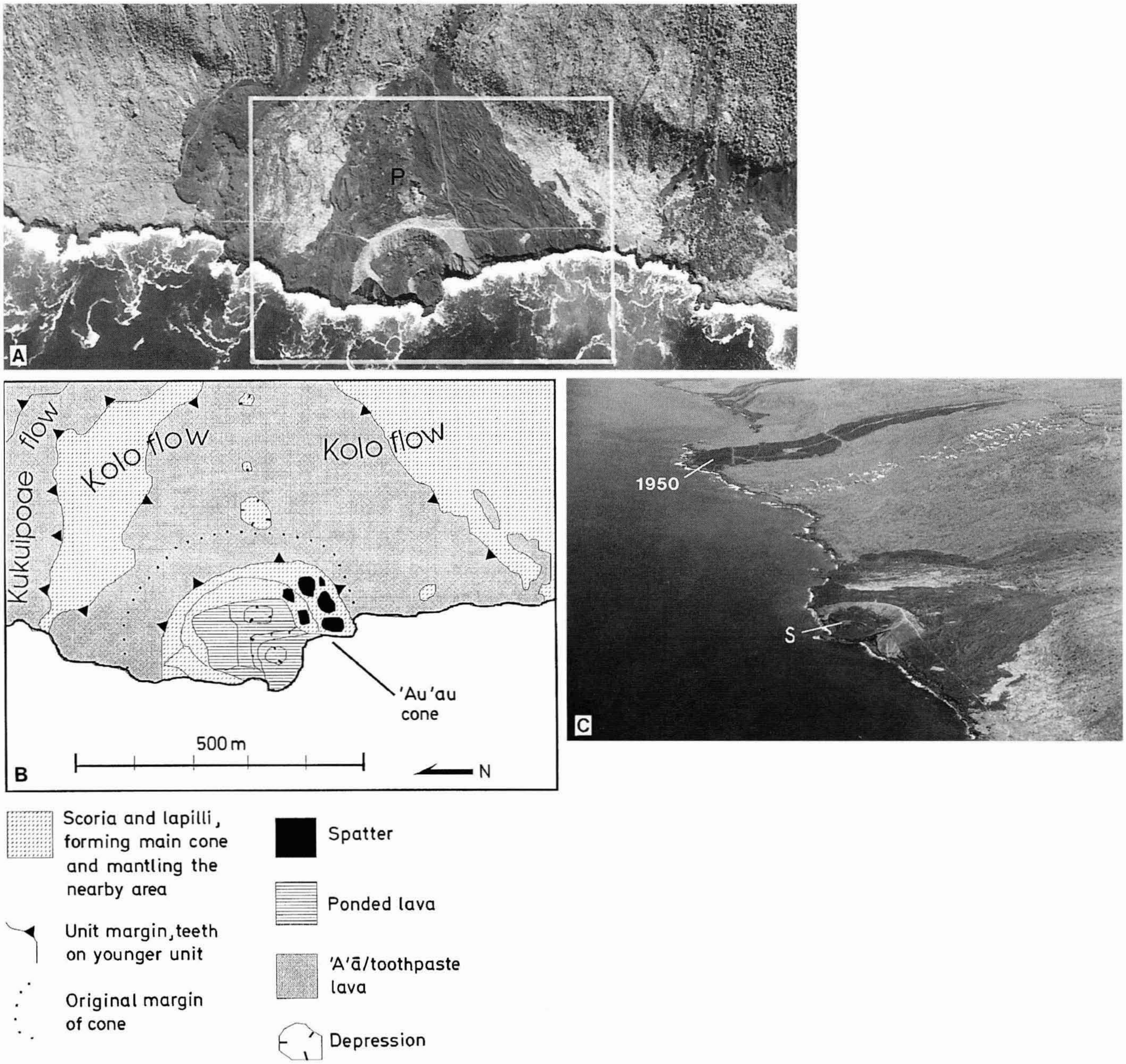

Fig. 7A–C 'Au'au Cone: **A** Vertical air photo (ASCS frame no. EKL 7CC 25). Note the relatively narrow fault-bounded coastal plain. *Box* indicates area of Fig. 7B, *P* indicates the once-upraised collapse pit in which are preserved light-toned main-rim pyroclastics (see text). **B** Geological map of 'Au'au cone. **C** Oblique air photo looking north (by J. P. Lockwood). Note the slightly lighter-toned spatter-mantled arcuate scarp (*S*). Beyond the Kona Paradise subdivision is the Kahoe flow (Lipman and Swenson 1984), erupted in 1950

formation of Pu'u Kī and Three-rim Cone is discussed later.

'Au'au Cone

'Au'au Cone forms 'Au'au Point, ~40 km NW of Pu'u Kī (Fig. 1). 'Au'au Cone occurs within the Kolo flow (Lipman and Swenson 1984), which is mostly pāhoehoe, but includes several later surges of 'a'ā and toothpaste lava. The structure of 'Au'au Cone (Fig. 7) is very similar to that of Three-rim Cone and Pu'u Kī in that it consists of an outer rim of lapilli and bomb-sized scoria and an interior of dense spatter and ponded lava. The outer rim stands 15–20 m above the surrounding Kolo lava flow and is about 200 m in diameter (Fig. 7). The outer rim of 'Au'au Cone also contains some spatter layers and many bombs and blocks that are up to a meter in diameter. The distal equivalent of the main rim can be followed S in the sea cliff, sandwiched between pre- and early Kolo flows and later Kolo 'a'ā. This deposit is 20–30 cm thick 350 m away from the center of 'Au'au Cone, and rests on clinker of a thick pre-Kolo 'a'ā flow. This same lapilli unit can be found over most of the nearby area. It supports vegetation much better than lava flows do, and particularly on the coastal plain it can be easily distinguished by the occurrence of light-colored grass (Fig. 7).

The lava flows within the main ʻAuʻau rim are 1–2 m thick with a total thickness of ~15 m. The flat-lying nature of these flows indicates that they ponded in what must have originally been a complete main rim of pyroclastics. Two minor collapse pits are found in the N part of the ponded lava flow. One way that ʻAuʻau Cone differs in detail from the two previous examples is that the ocean-facing scarp consists of two contrasting sections. The N part of this scarp is relatively straight and exposes cross sections of both the northern arm of the outer rim and the ponded flows. The S part of the scarp is strongly concave seaward and is mantled by a layer of dense spatter 1–2 m thick (Fig. 7).

A thin ʻaʻā and toothpaste lava flow issued from a jumbled and upraised area in the southern part of the cone, covered the floor of the cone, and flowed over the face of the arcuate scarp to form and/or mantle a small peninsula. Another series of late toothpaste lava flows originated from a once-inflated lava rise on the lava ~100 m east (and outside) of the main outer rim (Fig. 7). This lava rise subsequently collapsed to form a depression with an upraised margin. The margin was able to prevent burial of the depression by a later ʻaʻā flow; fine-grained pyroclasts associated with the main ʻAuʻau outer rim are preserved within this depression. A line of depressions and deep holes extends about 1 km farther up the slope and may indicate skylights and collapse pits along a lava tube. One of these openings shows evidence of having ejected spatter and it is probably a hornito. Alternatively, these features may mark an eruptive fissure.

Summary of cone structures

These three described cone complexes have in common: (a) an outer rim of lapilli- to bomb-sized scoria and spatter that either still is, or once was, a complete ring; and (b) one or more nested rims of dense spatter and associated lava that ponded within the outer rims. The two pyroclastic components indicate very different eruptive vigors that produced deposits resembling those of both primary Hawaiian and primary hydrovolcanic activity. Additional examples of cones similar in size and structure are the SE-most cone of the Pōhue Bay group near the toe of the 1887 flow (Fig. 2), and Puʻu Waimānalo, about 1 km northwest of Puʻu Hou (K. Hon, pers. commun. 1993).

Origin of the cones

The Pōhue Bay flow cones and ʻAuʻau Cone were originally regarded as littoral (e.g., Moore and Ault 1965) because they occur on the coast and because they are so far from any known rift zone that they are unlikely to be primary vents. However, their circular (or once-circular) form strongly resembles (primary) phreatomagmatic vents. Several lines of new evidence (Table 1; Jurado-Chichay 1993) support the secondary origin. Most notably, field evidence at Three-rim Cone (where the Pōhue Bay flow overlies the main rim and the latest spatter overlies the Pōhue Bay flow) ties the cone and flow to the same eruption. Paleomagnetic (Jurado-Chichay et al. 1996) and geochemical studies also indicate that Puʻu Kī, Three-rim Cone, and the Pōhue Bay flow are all part of the same eruption. Because the vent for the Pōhue Bay flow has been mapped 20 km upslope (Fig. 1; Lipman and Swenson 1984), the coastal cones must be secondary.

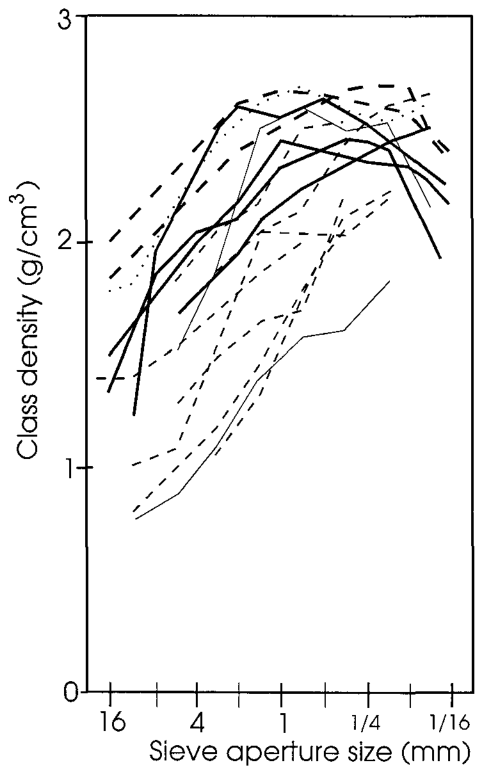

Fig. 8 Class densities of sieved samples as they vary with grain size, for Puʻu Kī (*heavy solid lines*), ʻAuʻau Cone (*heavy dashed lines*), and Sandhills littoral cone (*dotted line*). Also plotted are a number of other basaltic pyroclastic deposits from Walker (1992): Surtseyan ash cones (*light solid lines*), Strombolian cinder cones, and plinian deposits (*light dashed lines*)

Additionally, geochemical and density measurements show the pyroclasts of the cones to be degassed. S contents of the Puʻu Kī pyroclasts range between 30 and 140 ppm (samples collected and analyzed by D. Clague). These values contrast strongly with those of pyroclasts at primary vents (around 700 ppm S; Moore and Fabbi 1971) and are similar to those of lava flows (50–200 ppm S; Moore and Fabbi 1971; Swanson and Fabbi 1973; Sakai et al. 1982). The Puʻu Kī S values are therefore consistent with the pyroclastics being derived from a lava flow. The density of the spatter deposits at the Pōhue Bay and ʻAuʻau cones is higher than that of primary vents (Fig. 8), and it does not increase contin-

Table 1 Lines of evidence supporting a littoral origin for the cones discussed in this study. For a detailed discussion see Jurado-Chichay (1993)

Type of evidence	Description	Implications
Relationship between Pōhue Bay flow and cones		
Field relationships	Inner rim spatter overlies Pōhue Bay flow lava, and Pōhue Bay flow lava overlies main rim	Pōhue Bay flow and cones are part of the same eruptions which has a mapped vent area on the rift zone
Chemistry	Samples of lava ponded in cones and Pōhue Bay flow lava form a comagmatic trend	
Paleomagnetism	Mean directions of lavas ponded in cones and Pōhue Bay flow are statistically indistinguishable	
Sulfur contents	S contents of pyroclastics are lower than those of primary vents and similar to those of lava flows	Pōhue Bay flow and cones are degassed relative to primary vents
Density of pyroclasts	Densities are higher than those of primary vent deposits and show no density increase at small grain sizes. There is a continuum of density from uphill channel overflows (1.1 g/cm^3) to the coastal flows and spatter (1.5 g/cm^3)	
Location with regard to rift zones	Pōhue Bay flow cones are 15 km from the SW rift zones but somewhat in line with the upper part of the rift. ʻAuʻau Cone is 15 km south of the region of mapped radial vents	Cones are in regions of the volcano where eruptive vents have not been identified
Dense angular debris	The debris is mineralogically similar to the lavas but unlike observed portions of lava flows. Similar debris occurs at unequivocal littoral cones on both Mauna Loa and Kīlauea	Equivocal origin
Depressions uphill of ʻAuʻau Cone	A line of depressions, one of which has accumulated spatter around its rim	ʻAuʻau Cone and depressions might be vents

uously toward smaller grain sizes. This lack of increase has been used by Walker (1992) to indicate a degassed source (i.e., a surface lava flow) for particular pyroclastic deposits; beyond ~1/2 mm, further fragmentation does not greatly affect particle density.

Many of the pyroclastic deposits are spatter and coarse scoria (i.e., about half of Puʻu Kī itself, most of the south cone in the Puʻu Kī cluster, and about half of ʻAuʻau Cone), showing that the participation of water did not always strongly fragment the lava. All cones include conspicuous welded layers and rheomorphic spatter-fed flows indicative of high accumulation rates and low lava viscosities. The style of eruption must have at times resembled typical Hawaiian-style fire fountaining. During the ongoing Kīlauea eruption, littoral explosions have occasionally thrown material up to 100 m high (Mattox 1993, 1994; D. Clague, pers. commun.). At other times the activity consisted of less violent spattering (Fig. 9A). These events have produced circular littoral cones up to 15 m high and 40 m wide (Fig. 9B) that are constructed mostly of dense spatter blobs 10–20 cm across, many of which have cores of angular lava fragments, as well as ribbon bombs and some finer ejecta.

Several cones in our study area, notably the south cone of the Puʻu Kī cluster and ʻAuʻau Cone, experienced a change of eruptive style at the end of main-cone formation but prior to the final spatter activity. This is indicated by finer-grained poorly sorted pyroclastics (i.e., unit D in Fig. 4 and the light-toned grass-supporting unit in Fig. 7). Unit D at Puʻu Kī is conspicuously richer than the underlying layers in dense angular olivine-phyric debris; it appears that the final stage of main-cone building was the most explosive. The provenance of the olivine-phyric debris is somewhat problematic. If it derived from parts of the same flow that hosted the littoral activity (which is supported by the mineralogy), it indicates a degree of degassing not observed in surface lavas that may have taken weeks to months to achieve, perhaps within stagnated portions of the flow. Similar dense debris is common at Puʻu Hou (an unequivocal littoral cone), and lava blocks with densities up to 2.7 g/cm^3 have been ejected by the littoral explosions of the ongoing Kīlauea eruption (Mattox 1993). For the ongoing Kīlauea eruption, this density corresponds to ~7% vesicularity and 58% degassing during flow based on a vent lava vesicularity of 65% (Mangan and Cashman 1992). Conversely, the debris is derived from earlier underlying flows, and quarrying down into these flows would be required. Explosions at primary vents can easily quarry down, but it is difficult to see how littoral explosions can do so because the explosions originate at or near the lava–water interface.

The Pōhue Bay cones lie well off the southwest rift zone (Fig. 1). If the line of the rift zone above the 1800-m elevation is extended downslope, it intersects the coast near the Nā Puʻu a Pele cones. However,

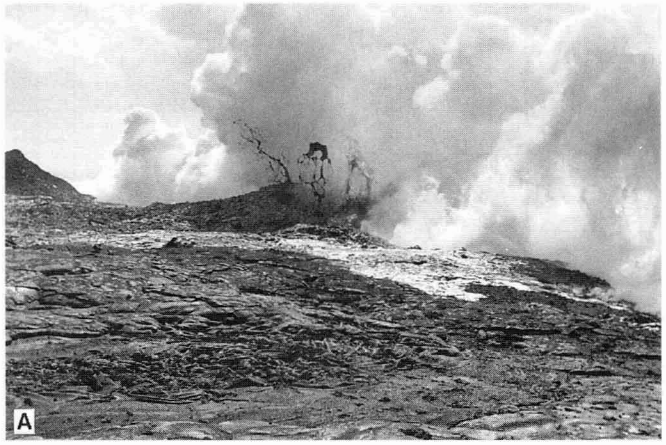

Fig. 9A, B March 1994 littoral activity of the ongoing Kīlauea eruption at the Lae 'Apuki ocean entry site: **A** active spattering to ~25 m (photo by V. Realmuto, Jet Propulsion Lab). Note an earlier littoral cone at left and shiny degassed pāhoehoe flowing toward viewer. **B** A small circular littoral cone 10–15 m across

there are no indications of eruptive vents along such an extension nor is there a topographic expression of a buried rift. Furthermore, such a hypothesis would imply an eastward migration of the lower rift zone to achieve its present configuration. Lipman (1980a, b) has shown instead that westward migration of the middle rift zone caused the observed bend. A class of non-rift-zone vents (radial vents; Lockwood and Lipman 1987) occurs on the northwest flank of Mauna Loa. 'Au'au Cone is about 15 km south of the southernmost of these (that of the 1877 Kealakekua Bay eruption; e.g., Moore et al. 1985).

The balance of evidence suggests that the Pōhue Bay cones are of littoral origin. However, the origin of 'Au'au Cone is a little more equivocal. The very close similarity between the forms of these cones and primary vent structures highlights the fact that diagnosis of the origin of such features is by no means straightforward.

Hypothesis for the formation of circular littoral cones

If we accept the littoral origin for the cones described herein, they do not conform to the traditional description of a littoral cone. Any formation scenario must explain their large size, (even though they are associated with pāhoehoe), their circular form, and the fact that they consist of both a lapilli/spatter outer rim with dense spatter and ponded lava within. The following scenario is based on our field work and is consistent with the mechanism to explain littoral activity during the Kūpa'ianahā/Pu'u 'Ō'ō eruption (Mattox 1993, 1994).

Initially, a tube-fed pāhoehoe flow approached the coastline across a preexisting coastal plain (Fig. 10A). A pāhoehoe lava delta of hyaloclastite and pillows formed when lava reached the ocean (Fig. 10B). Lava deltas consist of foreset beds of unconsolidated sand-sized hyaloclastite (formed as lava shatters upon contact with ocean water) intercalated with pillow lavas and pillow fragments (e.g., Moore et al. 1973). Collapses of the ocean edge of the lava delta occurred (e.g., Kauahikaua et al. 1993; Fig. 10C), accompanied by strong localized seismicity. At one or more points inland from the coast the tube collapsed either into the underlying water-saturated hyaloclastites (Fig. 10C) or into a water-filled void developed by wave undercutting. The mixing of the active tube and water or water-saturated hyaloclastites led to vigorous littoral explosions (Fig. 10D).

These explosions took place at an inland location allowing the buildup of complete rings of pyroclastics. The point of the explosions for the southwest Mauna

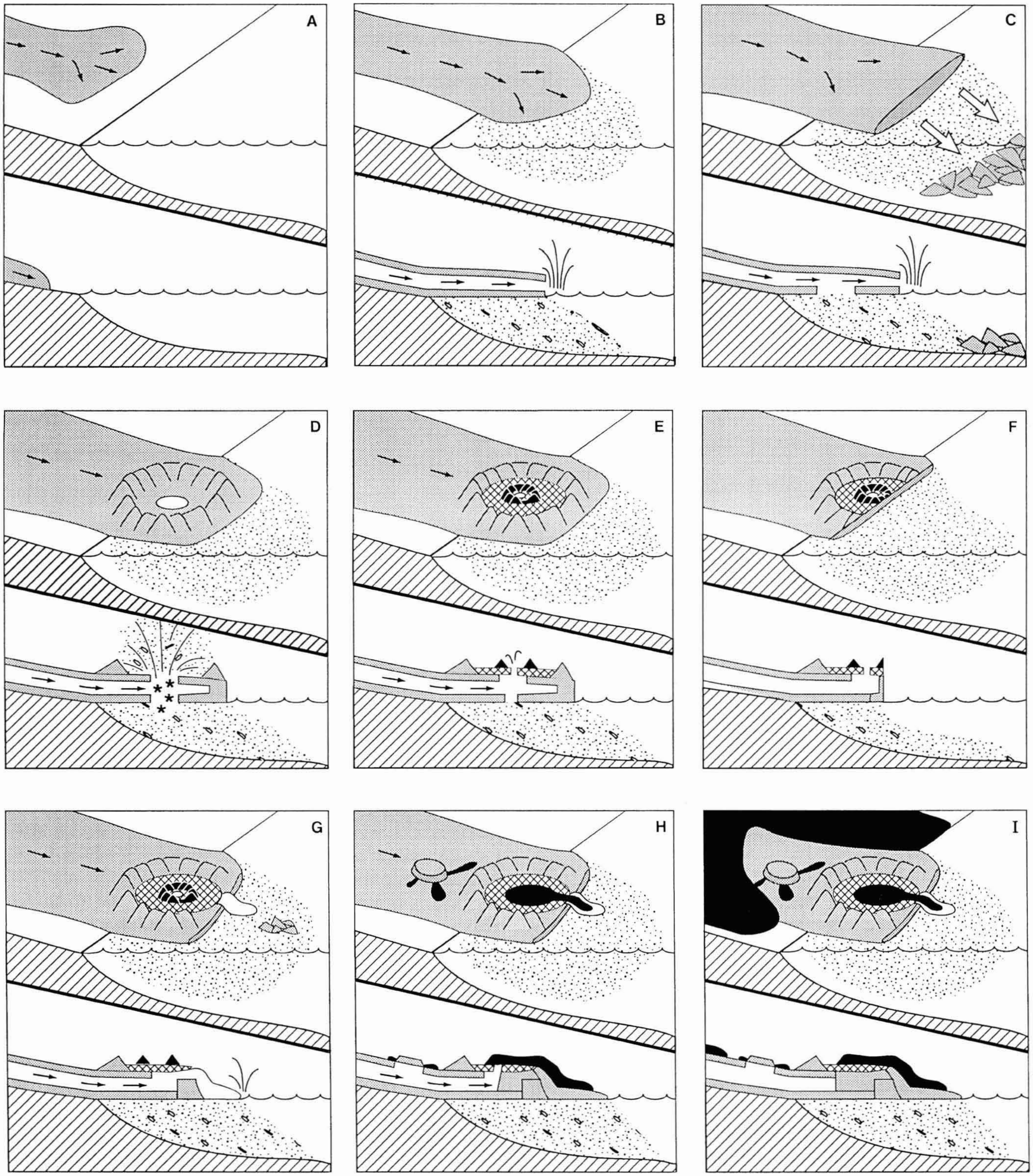

Fig. 10 Sequential diagrams (*upper boxes*) and cross sections (*lower boxes*) show the sequence of circular littoral cone formation: **A** Lava approaches the coastline. **B** Small littoral explosions form hyaloclastites over which the lava extends, forming a lava delta. **C** The front of the delta collapses. Inland, disturbances in the hyaloclastite allow the tube to collapse downward. **D** Molten lava mixes explosively with underlying wet hyaloclastites. Explosions (*asterisks*) break through the tube roof to start building the main littoral cone. **E** Water supply diminishes and explosions weaken to spattering and produce the inner rims (*black*), lava ponds within the main rim (*cross-hatched lines*). **F** Erosion/collapse occurs due to marine action (Pu'u Kī and Three-rim cone are at this stage). **G** At 'Au'au Cone – collapse takes place while molten lava remains in the ponded zone and a small lava flow extends oceanward accompanied by spattering. **H** Late-stage 'a'ā (*black*) occupies the tube and erupts through the ponded flows to cover the floor of the main cone and to mantle the small peninsula. Just uphill of the main rim a lava rise forms and leaks small 'a'ā and toothpaste lava flows (also *black*). **I** The last 'a'ā (*black*) surrounds the cone. (Figure drafted by N. Hulbirt)

Loa cones studied here was at least 2–4 m above present sea level and perhaps much farther inland (based on 1.8–3 mm/year of subsidence and a 1300-year age for the Pōhue Bay flow from the paleomagnetic data; e.g., Clague and Dalrymple 1987; Jurado-Chichay et al. 1996).

Wohletz (1983) and Morrissey (1990) demonstrate that the lava–water ratio determines the strength of explosions and therefore the size of the particles. Using these ideas we suggest that the fine-grained component of the main rims was formed during the strongest explosions. Occasional decreases in the amount of available water led to less-violent explosions and the formation of the intercalated spatter layers. At times, spatter accumulation was rapid enough to produce spatter-fed flows. The main cone built up on the solid flow surface, and lava could continue to be fed through the main tube. The final stage of main-cone building was the most explosive and produced the upper layer rich in angular fragments that is widely dispersed in both the Pu'u Kī and 'Au'au Cone areas.

At some point the water-to-lava ratio decreased greatly as did the vigor of the explosions (Fig. 10E). Dense spatter and lava began to fill the newly created main rim. Activity within the main flow field continued, overlapping the outer base of the cones.

Eventually, supply of lava to this area ceased, and activity migrated along the coast to repeat the process. Wave action at both Pu'u Kī and Three-rim Cone eroded the seaward parts of the outer rims to expose the ponded/spatter-fed lava (Fig. 10F). At 'Au'au Cone, however, the collapse of the seaward section took place while there was still molten lava in the ponded zone. This lava flowed into the ocean to form a small peninsula (Fig. 10G) and generated littoral explosions which threw out blobs of spatter that mantled the arcuate scarp and the S half of the cone. Still later at 'Au'au Cone, lava reoccupied the tube, forcibly extruded 'a'ā and toothpaste lava into the cone interior, and resurfaced both it and the small peninsula (Fig. 10H). This same lava also issued from the lava rise (now a collapse pit) just upslope of the main rim. An even later 'a'ā flow bifurcated around 'Au'au Cone (Fig. 10I).

An additional feature at Pu'u Kī and Three-rim Cone is the large collapsed lava rise just inland from the cones (Fig. 2; Jurado et al. 1991). We calculate that this lava rise could have stored $\sim 500{,}000\ m^3$ of lava. If this volume of stored lava drained out suddenly, it could have augmented the volumetric flow rate into the ocean that built Pu'u Kī and Three-rim cone, leading to their large size. Even without the draining of this depression, the Pōhue Bay flow may have had a volumetric flow rate higher than that observed for historical tube-fed flows (5–20 m^3/s; Rowland and Walker 1990). A major channel/tube system occurs in the Pōhue Bay flow 2–4 km inland. Calculations (e.g., Jurado-Chichay 1993; Jurado-Chichay and Rowland 1995) suggest that volumetric flow rates in this part of the flow ranged from around 80 m^3/s and possibly were as high as 900 m^3/s.

These are even higher than most historical Mauna Loa 'a'ā flows (e.g., Rowland and Walker 1990). This high discharge of lava was distributed into multiple flows on the coastal plain, and thus no ocean entry received the full lava flux. However, the lava flux into the ocean was probably much higher than that seen in historic tube-fed pāhoehoe eruptions.

Conclusions

We have described a number of near-circular cones, each consisting of an outer rim 100–400 m in diameter composed mostly of lapilli and spatter and one or more cones nested inside that are composed of dense spatter. These structures are closely associated with pāhoehoe lavas, and using a variety of evidence we conclude that they are littoral in origin. The essential requirements for forming circular littoral cones are (a) a tube-fed pāhoehoe flow; and (b) efficient mixing of the lava and water at an inland location (i.e., in the underlying hyaloclastites of a lava delta).

The lava flow involved in the formation of circular littoral cones must be tube-fed, which in Hawai'i is always pāhoehoe. A tube-fed pāhoehoe flow allows littoral pyroclasts to build up in all directions around the point of explosions. Any flow with an open channel or moving top surface (such as 'a'ā) will carry away the littoral pyroclasts that land on it, either onshore or offshore, and the result will be the more familiar pair of half cones on either side of the lava. Additional evidence for the close association with pāhoehoe is the nature of the spatter deposits. In order to form spatter, the lava must have a low viscosity, and this rules out the possibility of viscous 'a'ā. The rootless cones of Iceland are also associated with tube-fed lavas and have been inferred to form in a manner similar to that proposed here for the Pōhue Bay flow cones and 'Au'au Cone (Morrissey and Thordarson 1991; Thordarson and Self 1993).

The circular littoral cones recently observed forming on Kīlauea (Fig. 9; Mattox 1993, 1994) have been much smaller (about 20–30 m in diameter) than those described in this paper. This Kīlauea eruption has had a relatively constant volumetric flow rate of $<5\ m^3/s$ (Mattox et al. 1993). We suggest that the main reason why Pu'u Kī, Three-rim, and 'Au'au cones are larger is that they were associated with higher volumetric flow rates.

This study has shown that the differences between secondary and primary cones are not always obvious. It is important, therefore, to study their diagnostic features. The interpretation of these cones as littoral is not completely unequivocal because they resemble primary vents in many ways. If they are indeed primary, they have important consequences with respect to expected eruption locations on Mauna Loa. Regardless of their origin, formation of similar cones in the future would present a significant volcanic hazard at coastal locations.

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