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Puu Mahana Near South Point in Hawaii Is a Primary Surtseyan Ash Ring, Not a Sandhills-type Littoral Cone[1]

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ABSTRACT: Puu Mahana has previously been interpreted to be a littoral cone, formed at a secondary rootless vent where lava flowed from land into the ocean, but a number of lines of evidence point to it being a remnant of a Surtseyan tuff ring built on a primary vent. The differences between it and littoral cones are highlighted by a comparison of Puu Mahana with the undoubted littoral cone of the Sandhills that was observed to form in the 1840 flank eruption of Kilauea Volcano. Puu Mahana contains abundant lithic debris and accretionary lapilli, absent in the Sandhills deposit. Compared with the Sandhills, the Puu Mahana pyroclastic deposit is finer grained and more poorly sorted, and its juvenile component is less dense and more highly vesiculated. Puu Mahana lies 3 to 4 km off Mauna Loa's southwest rift zone. Identification of it as a primary vent implies that the lower rift zones of Hawaiian volcanoes can be much wider and more diffuse or more mobile than is currently acknowledged. The olivine grains that compose the well-known green-sand beach at Puu Mahana are likely derived from the ash, strongly concentrated and somewhat abraded by wave action.

PUU MAHANA, A SMALL coastal hill situated 5 km northeast of South Point on the island of Hawaii, is an upstanding portion of the rim of an ash cone that has been partly buried by basalt lavas. Previous workers considered that Puu Mahana is a littoral cone formed by explosions at a secondary or rootless vent where lava flowed from land into water, but a critical reexamination indicates that the cone was formed by a Surtseyan-style eruption at a primary vent. Nearby Mahana Bay formed by preferential erosion of the ash. It is well known for its green olivine-rich beach sand, perhaps the finest example in Hawaii. This study includes data on the green sand.

Puu Mahana was identified as a littoral cone by Wentworth (1938), Stearns and Macdonald (1946), Wentworth and Macdonald (1953), Macdonald and Abbott (1970), and Macdonald et al. (1983). The occurrence was fully described by Wentworth (1938), who drew a contour map of the cone. Historical littoral cones in Hawaii were described by Moore and Ault (1965), and a detailed description including grain size analyses of Puu Hou, the littoral cone group formed by the 1868 eruption of Mauna Loa, was given by Fisher (1968). A general discussion of the diagnostic features of littoral cones was given by Macdonald (1972). He pointed out that the ash grains are usually denser and contain fewer bubble-wall shards than those of primary vents; how dense the fragments are depends on how far the lava has traveled before reaching the sea. He also noted that the explosive activity that generates littoral cones preferentially occurs on aa lava flows, and suggested that the rough rubbly surface of aa provides many channels for ingress of water and promotes explosive activity.

To illustrate the characteristics of primary Surtseyan deposits and the differences between them and littoral cones, a direct comparison is now made between Puu Mahana and the unambiguous littoral cone of the Sandhills (Puu Nanawale) in the Puna District on the north coast of Kilauea. Sandhills is the

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most accessible littoral cone in Hawaii, formed by explosions where the lava flow of 1840 entered the ocean. Identification of Puu Mahana as a primary vent structure has important implications regarding the position and width of Mauna Loa's southwest rift zone.

THE PUU MAHANA CONE

Puu Mahana is about 38 m high, but this is a minimum height value since the base of the deposit extends an unknown distance below sea level. The Sandhills deposits are smaller: they rest on a lava platform and rise only 25 m above it. This is also a minimum value, however, since the dip is inland and the centers of the original ash cones were situated some distance offshore and have since been eroded away.

As shown by the map of Wentworth (1938), Puu Mahana is an ash ridge about 250 m long by 120 m wide, the long axis of which trends roughly northwest at right angles to the coast. The ridge is abruptly truncated by, and is well exposed in cross section in, the coastal cliff. The well-known green sand beach occurs at the foot of this cliff. Younger basaltic lava flows overlap onto the ashes on both sides of the ridge. Mahana Bay is a broad slot between these lavas and occupies the seaward extension of the ridge where the ashes were preferentially eroded out by the ocean.

Puu Mahana consists of well-bedded to laminated ash deposits having a southwestward dip of 10° to 20° (less than the angle of repose of loose pyroclastic materials). It is apparently a small segment of an ash ring, the remainder of which is either buried or eroded away. The boundary between ash and overlapping basalt is steeper, about 40°, on the northeast side of the ridge (Figure 1*c*). This steeper slope is regarded as the inner wall of a crater. Angular to subangular lithic fragments consisting of various basalt types are dispersed widely through the deposit. The largest, about 50 cm, are concentrated on the steep northeastern side and tend to confirm that this is the inner wall of a crater.

Two younger basaltic flows overlap onto Puu Mahana ash on both sides of Mahana Bay. The upper lava on the southwestern side and both lavas on the northeastern side contain abundant tree molds up to 16 cm in diam. at or near their base, showing that a considerable time interval elapsed between the Puu Mahana eruption and the formation of these basalts. Puu Mahana is moreover mantled by Pahala ash, suggesting that it is a relatively old feature. A carbonaceous soil at the base of one of the overlying lavas yielded a ^{14}C age of 28,000 yr (sample W4368, Rubin et al. 1987). Puu Mahana therefore exceeds 28,000 yr in age. At the known subsidence rate of Hawaii (Moore 1987), it has probably subsided by at least 67 m since it formed. The visible part of Puu Mahana is thus the top of a much larger structure. This is reasonable: the primary tuff rings of Diamond Head and Koko Crater on Oahu are respectively 232 m and 368 m high.

The classic line of evidence for a littoral cone, namely the occurrence of two part-cones on either side of a lava corridor, with synchroneity of the part-cones and lava, is not available at Puu Mahana because only one cone remnant is visible. The question of whether or not it is a littoral cone must, therefore, depend on other lines of evidence.

Four channel samples and eight samples of single beds were collected from different levels to characterize the deposit. Each channel sample was collected across about 2 m of deposit thickness from a narrow-cut channel of approximate uniform depth and width so as to be representative of that thickness. These samples were sieved employing a set of sieves having a 1-phi aperture spacing (Inman 1952). Bulk-sample and class densities (the density of material in each grain size class) were obtained by weighing the samples and estimating their volumes in graduated cylinders; an empirical correction to the class densities was applied for intergrain voids. Component analyses were performed on some samples.

The ash deposit is incipiently lithified. The finest beds and fine aggregates (e.g., accretionary lapilli) are most strongly lithified probably because of the large surface area of small grains and the narrowness of the capillaries between them. Complete disaggregation of some samples for sieving was not achieved.

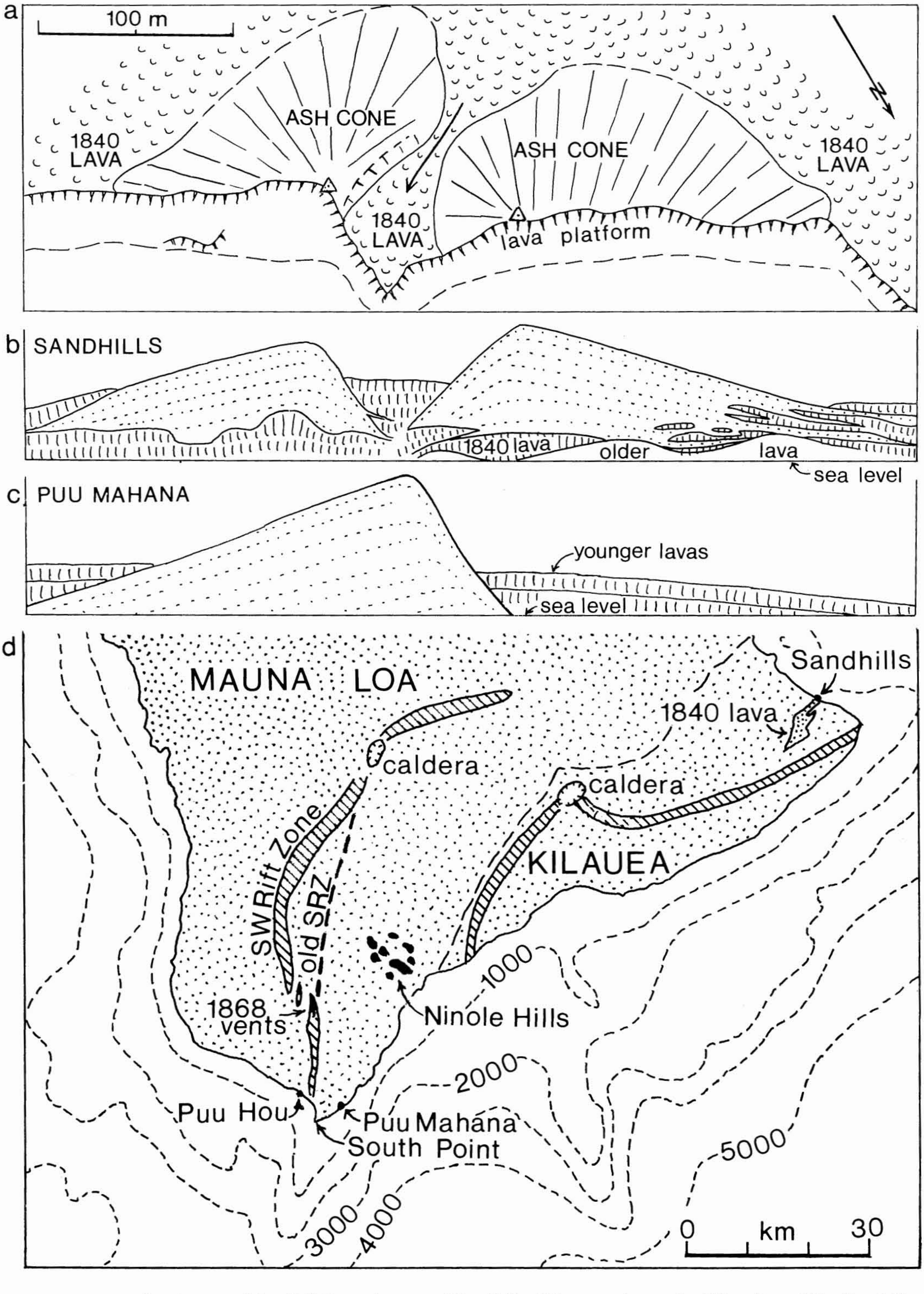

FIGURE 1. *a*, Sketch map of the 1840 littoral cones of Sandhills, Kilauea volcano; *b*, cliff section of the Sandhills littoral cones, vertical exaggeration × 2; *c*, cliff section of the Puu Mahana cone, on the same scale as *a* and *b*; *d*, index map of part of the island of Hawaii showing the locations of sites mentioned in the text. Old south rift zone after Lipman et al. (1990). Dashed lines: isobaths, at 1000-m intervals.

THE SAND HILLS LITTORAL CONE

The Puu Nanawale (Sandhills) ash deposit extends about 400 m along the north Puna coast and consists of two asymmetric part-cones nearly equal in size separated by a narrow corridor of basalt lava (Figure 1*a*, *b*). The western cone rises to about 36 m above sea level, and the ash attains a maximum thickness of about 25 m. The eastern part-cone is slightly lower, and the ash is slightly thinner. The ash of both part-cones rests on the lowest flow units of the 1840 lava.

At each end of the coast section the ash is seen to thin rapidly. Basalt flow units overlap onto it, and some ash is interbedded with lava flow units. Interbedding with lava is also seen within part of the western cone. Basalt of the corridor that separates the two part-cones overlaps onto the ash with minor interbedding. These overlapping contacts are much steeper than the outer ones, and the eastern part-cone rises particularly steeply above the corridor, suggestive of erosion and undercutting of ash by the flowing lava. The ash is baked to a bright red color in places where basalt rests on it.

It is apparent from the 30° to 35° inland dip of the ash that the centers of the part-cones lay seaward of the present coast and have been eroded away. The eyewitness account by the Rev. Titus Coan (Brigham 1909) recorded that "three hills of scoria and sand were (also) formed in the sea, the lowest about 200, and the highest about 300 ft. high.... The sand hills thrown up at this place were found to be 150, and 250 ft. high eight months after their formation, but since then the sea has removed the whole mass [*sic*]. Even in 1865 they were not a third of the measured height." Survival of the part-cones that remain on this northward-facing coast, exposed as it is to the trade winds, is clearly due to the fact that the ash rests on a platform of erosion-resistant basalt lava. The ash itself is completely loose and shows no observed sign of lithification.

The olivine-rich 1840 lava of the platform below the western part-cone overlies an olivine-poor lava interpreted to be a pre-1840 flow. The 1840 lava below the eastern part-cone locally has a steep seaward slope and smooth upper surface and appears to have flowed down and mantled a cliff. The pre-1840 coastline was thus slightly seaward of the present coastline at the western part-cone and coincident with it at the eastern cone. The fact that the lowest ash rests on this lava platform and the centers of the part-cones are seaward of the present coastline indicates that the main explosive activity did not begin until the lava had flowed some distance north of the present coastline.

The ash deposit is rather poorly bedded and grain size variations between beds are rather small. In detail the thickness of some beds varies laterally, suggestive of deposition from weak base surges or in a strong wind. Some beds are predominantly made of ash-grade particles, but their content of fine ash is very low. The coarsest beds contain abundant basalt fragments several centimeters in size accompanied by much ash-grade material. All the pyroclastic material is juvenile, and olivine is a prominent constituent.

Five channel samples and eight samples of single beds were collected to characterize the deposit. One channel sample each was collected from the upper and lower part of each part-cone, plus one from a finer-grained basal part of the eastern cone. An important feature of the pyroclastic material is its high density and weak vesicularity. The class-density and sample bulk density values of the Sandhills deposit are higher than for any sampled deposits of primary-vent cinder cones or ash rings in Hawaii and the Azores (Figure 2).

Bombs range in size up to about 35 cm and have an irregular cauliflowerlike shape. The irregular shape results from centimeter-sized vesicles that are absent from most outcrops of 1840 lava and appear to be due to the penetration into the lava of steam generated from seawater. The more general millimeter-sized vesicles are similar in size to those in the lava crust and were already present in the lava when it entered the ocean. Some flow units of the lava are pahoehoe, and others are aa.

DIFFERENCES BETWEEN THE PUU MAHANA AND SANDHILLS DEPOSITS

The following differences are exhibited between the Puu Mahana and Sandhills deposits.

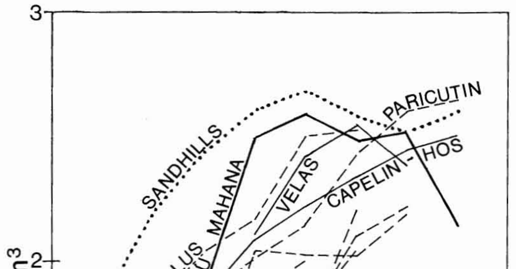

FIGURE 2. Class densities of sieved samples, as they vary with grain size, for Puu Mahana, Sandhills, and a number of other basaltic pyroclastic deposits. Solid lines: Surtseyan ash rings (Capelinhos 1957–1958, Faial, Azores; Velas, San Jorge, Azores; Karl, Reykjanes, Iceland). Dashed lines: Strombolian cinder zones and basaltic plinian deposits (Tantalus, Oahu, Hawaii; Paricutín, Mexico; Tarawera 1886, New Zealand; Fogo scoria cone, San Miguel, Azores; Etna 1974 flank vent; Mt. Rossi 1969, Etna; Heimaey 1973, Iceland).

It is not known to what extent these differences are specific to these two particular occurrences or are applicable to primary Surtseyan and rootless littoral cones in general.

LITHIC CONTENT. Puu Mahana contains conspicuous lithics, whereas Sandhills contains none. The lithics are angular and include a variety of basalt types. They occur mostly as blocks up to 50 cm, and ash-grade lithics consitute only a very small proportion (about 2%) of the deposit. Surtseyan tuff rings invariably contain lithics, presumed to have been derived from vent walls, and the absence of lithics from Sandhills is consistent with the very superficial nature of littoral explosions and failure of littoral vents to cut down into older rocks.

OCCURRENCE OF ACCRETIONARY LAPILLI. Pea-sized accretionary lapilli are abundant at all levels in the Puu Mahana deposit, but appear to be absent from the Sandhills deposit. I follow Moore and Peck (1962) in interpreting most accretionary lapilli, including many of the Puu Mahana ones, as resulting from the capture and accretion of ash by raindrops falling through an ash cloud. Accretionary lapilli having this origin require a combination of three circumstances, namely, a plentiful supply of fine ash, rain, and an ash cloud sufficiently high or sufficiently dense to enable falling raindrops to capture enough ash particles. To survive, accretionary lapilli must also be fairly dry when they land, otherwise they splash or break up on impact with the ground.

Rain may well have fallen during both the Puu Mahana and Sandhills eruptions, but it is surmised that a low content of fine ash and inadequate cloud height account for the lack of accretionary lapilli in the Sandhills deposit.

VESICULARITY OF JUVENILE CLASTS. Juvenile material in the Puu Mahana cone includes fragile pumice up to about 10 cm having a density of 0.7 mg/m^3 or less. Dense and poorly vesiculated blocky clasts also occur. The occurrence of highly inflated pumice is characteristic of Surtseyan tuff rings and is consistent with the maintenance of explosive eruption by internal vesiculation of the magma. Pumice is absent from the Sandhills deposit, and the uniformly high density of the ejecta (Figure 2) is consistent with their derivation from lava that had earlier passed through a stage of intense vesiculation (at its primary vent, inland) and had lost most of these vesicles; it was vesiculating only slightly if at all at its secondary vent, although centimeter-sized vesicles were forming where vaporized seawater entered the lava.

DENSITY VARIATION WITH CLAST SIZE. When pyroclastic deposits are sieved, the class densities increase as the grain size decreases (Figure 2). The main reason is that the vesicle population has a wide size range, and as clasts decrease in size they are capable of enclosing only the vesicles in the ever-finer fine tail of this population. The rate of change of class density crudely reflects the vesicle population, except that when the erupted magma is porphyritic a density peak may occur in the grain size classes in which the dense crystals occur.

The rate of change of class density for Puu Mahana is normal for pyroclastic deposits at primary vents where the magma has a youthful vesicle population. The maximum rate of change for Sandhills occurs at larger grain sizes than is normal for deposits of primary vents, reflecting derivation of the clasts from a lava flow that had a mature vesicle population but gained large vesicles from vaporized seawater.

STATE OF LIBERATED CRYSTALS. Both Puu Mahana and Sandhills contain abundant olivine crystals liberated from the magma (Figure 3). In the Puu Mahana ash about half of them are euhedral and unbroken and retain a thin layer of glass with bubble-wall texture on their surface. In contrast, practically all in the Sandhills deposit are broken grains, consistent with fragmentation of less vesicular lava. The difference could alternatively be due to a higher viscosity of the 1840 Sandhills lava. Trusdell (1991) commented on the uniform content of olivine phenocrysts in this lava, a feature that implies a relatively high lava viscosity (Rowland and Walker 1988).

CONTENT OF FINE ASH. The content of fine ash (finer than 63 μm) in basaltic pyroclastic deposits depends partly on how much external water participates. It is typically very low in Strombolian-style deposits and high in Surtseyan ones (Walker 1973). The Sandhills, although not a typical Strombolian deposit, resembles one in containing a negligible proportion (about 1% wt in channel samples) of fine ash. Channel samples from Puu Mahana have much more (average nearly 10%), typical of but somewhat less than for other Surtseyan ash rings. It compares with average values of 13% for the Karl ash ring in Reykjanes, Iceland, and 19% for the 1957–1958 Capelinhos ring in Faial, Azores. Puu Mahana is slightly lithified, so that complete disaggregation is difficult, and the amount of fine ash in analyzed samples is underestimated.

Channel samples reveal that the Puu Mahana deposit is consistently finer grained than the Sandhills deposit (Figures 3, 4). In windy weather a proportion of the fine erupted ash is blown away and deposited outside the limit of the cone; no information is available on these distal deposits of either Puu Mahana or Sandhills, and whole-deposit grain size populations cannot therefore be determined.

GRAIN SIZE PARAMETERS OF PYROCLASTIC BEDS. Each bed in a pyroclastic deposit has a grain size distribution that can be characterized by such parameters (following Inman 1952) as the median grain diameter (Md) and graphic standard deviation (σ), the values of which have some diagnostic value. Walker and Croasdale (1972) showed that Surtseyan and Strombolian beds plot on different fields on an $Md\phi/\sigma\phi$ plot, reflecting significant differences in the grain size populations and depositional mechanisms (Figure 5).

The Puu Mahana samples plot in the Surtseyan field, whereas Sandhills samples (and also samples from the Puu Hou littoral cone: Fisher 1968) plot astride the Surtseyan/Strombolian field boundary.

CONE SLOPE ANGLE. In weak explosive eruptions the pyroclasts fall preponderantly very close to the eruptive vent; their redistribution by gravity then generates steep-angle cones sloping at the angle of repose (33°–36°) of loose materials, exemplified by typical cinder cones of Strombolian-style eruptions. As eruption power increases, the fallout is more widely dispersed and low-angle cones standing at less than the angle of repose result. Puu Mahana is such a low-angle cone: its eruption was more powerful than that of Sandhills, consistent with it being a primary vent structure.

ORIGIN OF THE GREEN-SAND BEACH

Sieve and component analyses of two samples of the Mahana Bay beach sand give Md of +0.6 and +1.1 phi (0.66 and 0.47 mm,

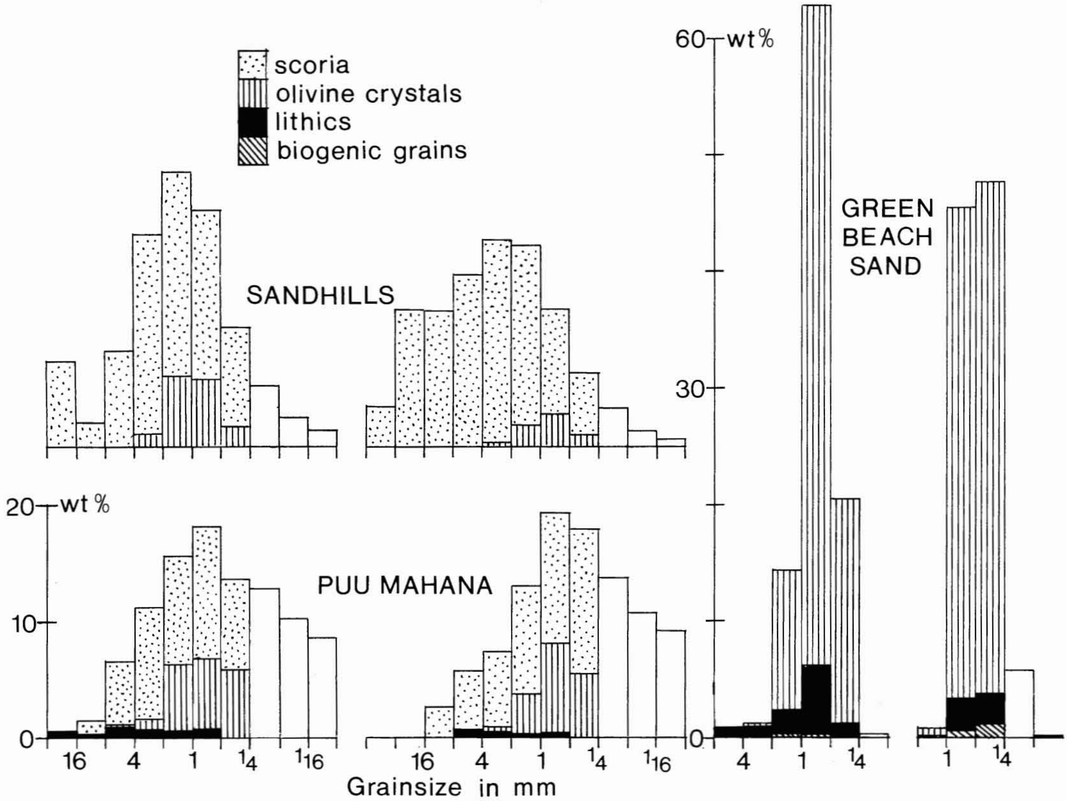

FIGURE 3. Grain size histograms of channel samples from Puu Mahana and Sandhills (note lesser amount of fines in the latter) and two samples of olivine-rich beach sand from Puu Mahana. The bars for $\frac{1}{4}$ mm and coarser are subdivided to show the proportions of their components.

respectively) and a graphic standard deviation (σ) of 0.55 to 0.5 phi (Figures 3, 4). These values are normal for beach sands. Crystals (mostly olivine; also some pyroxene) constitute 88 and 92% wt, respectively, of these samples. They are well rounded. Coarse pumice from the Puu Mahana ash when crushed yields 17% wt of olivine having a maximum diameter of 3 mm and a median of +0.3 phi (0.81 mm). An almost identical olivine population occurs in channel samples on which component analyses were performed (Figure 4).

This is consistent with the olivine in the beach sand being derived from erosion of the ash, suffering a general reduction in diameter of 20 to 40% by abrasion, and being enriched by a factor of 44 as prolonged wave action selectively removed the less-dense components (enrichment factor = $C_2/P_2 \times P_1/C_1$, where C_1 and P_1 are weight percentages of crystals and pumice in crushed pumice, and C_2 and P_2 are weight percentages of these components in the concentrate). The lava flows on either side of Mahana Bay are rich in olivine and may have contributed to the beach sand.

IMPLICATIONS

The foregoing data collectively point to Puu Mahana as being a remnant of an ash cone resulting from a Surtseyan-style eruption at a primary vent. A number of differences between Puu Mahana and Sandhills are documented. Some may be specific to these two particular occurrences and may not be general differences diagnostic of primary Surtseyan

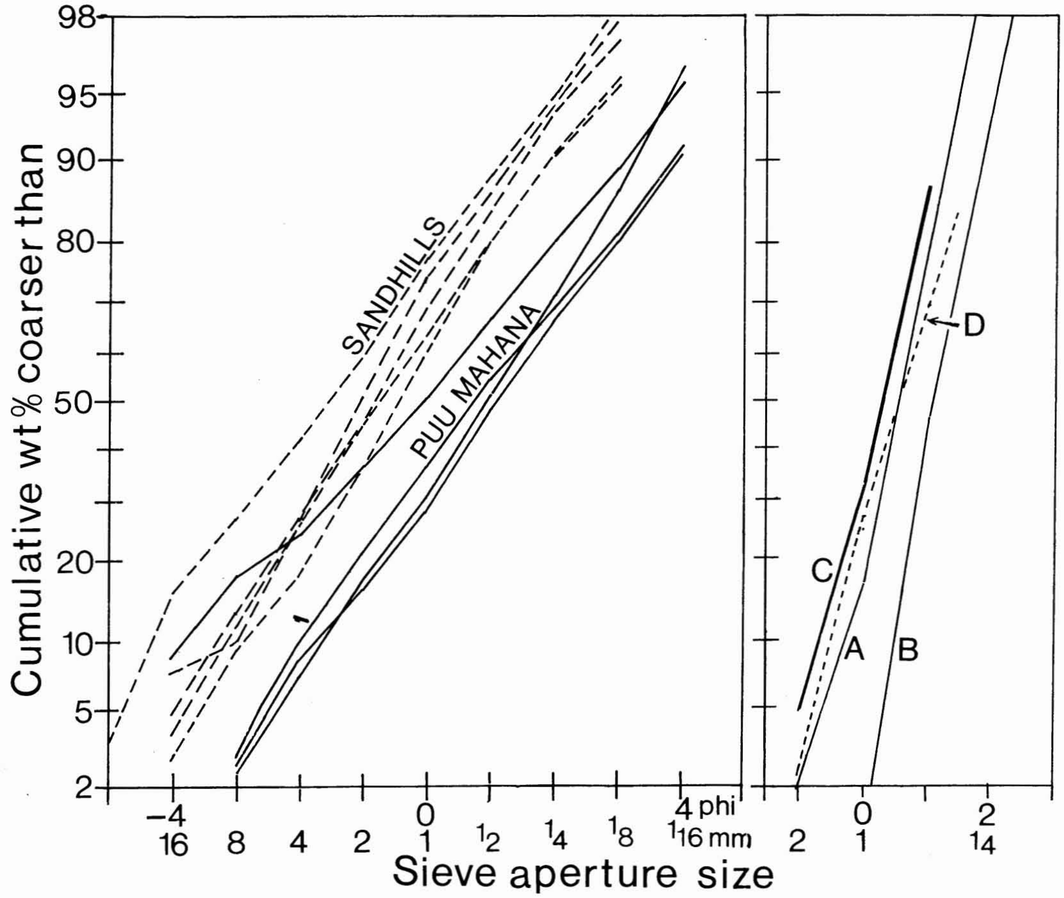

FIGURE 4. Plots on probability graph paper showing grain size distributions. *Left*, channel samples from Puu Mahana and Sandhills; the latter are systematically finer. *Right*, A and B, two samples of olivine-rich beach sand from Puu Mahana as in Figure 3; C, olivine population separated from crushed pumice of Puu Mahana; D, olivine population in two channel samples (averaged) of Puu Mahana ash.

versus rootless littoral origin. Probably a spectrum of types with gradational characteristics exists, depending on the volumetric flux of lava, the relative fluxes of lava and water (Wohletz 1983, 1986), and how intimately lava and water are intermingled.

Recognition of the primary-vent origin of Puu Mahana has important implications regarding the position and width of Mauna Loa's southwest rift zone. Puu Mahana lies 3 to 4 km east of the rift zone and may indicate that the rift zone is much wider than is currently recognized. It is, however, consistent with a trend pointed out by Lipman (1980*a*, *b*) and Lipman et al. (1990) marked by a progressive westward lateral shift of the rift zone (away from Kilauea, inferred to have acted as a barrier to symmetrical growth). If, as was suggested by Lipman (1980*a*), the anomalous Ninole Hills mark an earlier flank of Mauna Loa, Puu Mahana represents a westward migration by about half of the distance from the Ninole Hills to the present rift zone.

Puu Mahana is also about 17 km farther south than the southernmost documented historical primary vent on Mauna Loa (that of the 1868 eruption). This is consistent with another trend, documented by Moore et al.

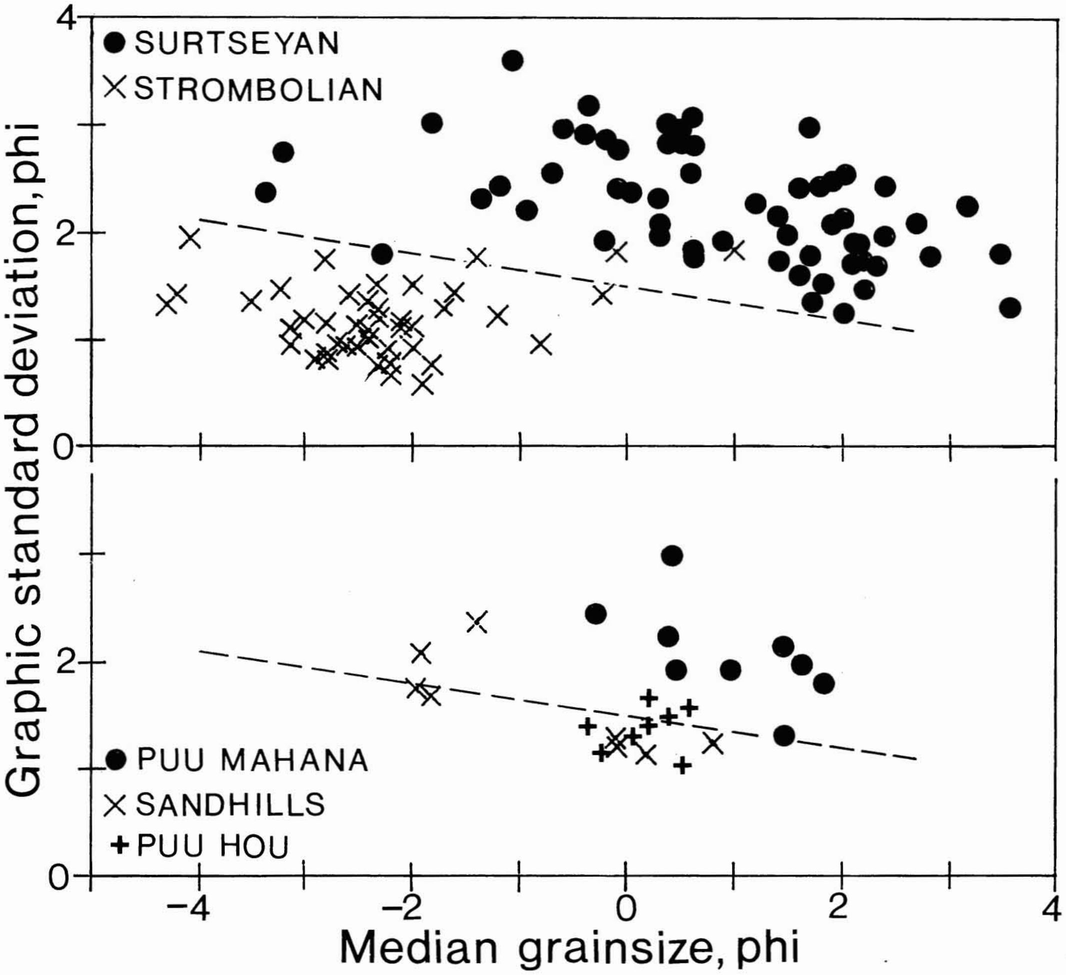

FIGURE 5. Plots of graphic standard deviation (σ) against median grain diameters (Md) of sieved samples of single beds. *Above*, from typical Surtseyan ash rings and Strombolian cinder zones (Walker and Croasdale 1972); dashed line delineates approximate boundary between fields. *Below*, Puu Mahana samples plot in the Surtseyan field; Sandhills and Puu Hou (Fisher 1968) littoral cone samples straddle the Surtseyan/Strombolian field boundary.

(1990), of rift zone activity becoming increasingly restricted toward the upper part of Mauna Loa (a condition possibly heralding the end of the shield-building stage of activity).

ACKNOWLEDGMENTS

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