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Accretionary lapilli beds in the Keanakak'oi Ash: footprint-bearing beds not 1790 in age

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Field investigation of Keanakak'oi accretionary lapilli beds: correlation between proximal and distal layers

Location of exposures visited

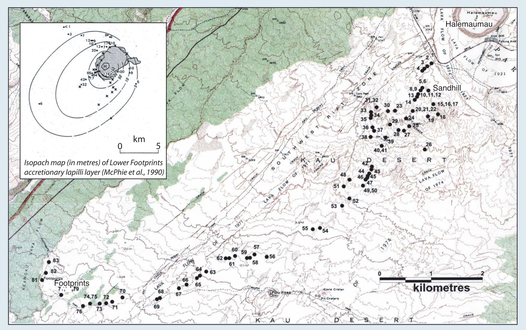


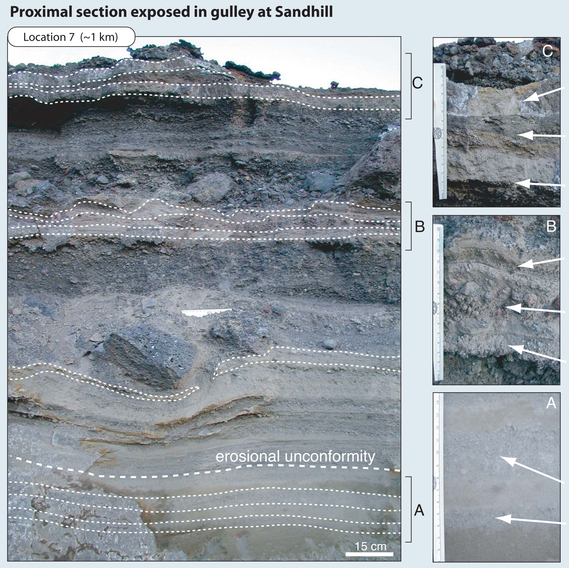
Fig. 1 Keanakak'oi Ash exposure locations investigated: Kau Desert, Southwest Rift Zone, Kilauea

The Keanakak'oi Ash is the product of explosive volcanic activity at Kilauea volcano between about A.D. 1500 and 1790. Accompanying the deposits from the eruption are thin, massive, fine ash layers a few centimeters thick containing accretionary lapilli. Human footprints are preserved in two fine ash layers (Upper and Lower Footprints ash layers) abundant in accretionary lapilli at many places within 10 km southwest of Halemaumau Crater.

Translations of Hawaiian legend talk of an eruption that killed 80-800 members of a war party near Kilauea's summit caldera in recent times (Westervelt, 1966). Pioneering investigations into the stratigraphy of Keanakak'oi Ash by early HVO researchers suggested that the footprints were left by the Hawaiian war party as they fled eruptions in 1790 (e.g. Jaggar, 1930). More recent work (e.g. Christiansen, 1979) suggested that all of the Keanakak'oi Ash was deposited in 1790 and major unconformities present in the succession are the result of surge-flow erosion without a significant break in time. McPhie et al. (1990) recognised three main eruptive phases, and suggested the whole sequence was deposited in weeks to months.

This current investigation presents some important observations that implies the Footprints layers are separated by a depositional hiatus of years, maybe centuries. The presence of human footprints in both layers also suggests that Hawaiians were active in the area on a regular basis, contrary to popular belief.

Proximal section exposed in gulley at Sandhill



7 accretionary lapilli horizons in the upper proximal section

C: accretionary lapilli horizon forms impact sags into massive fine ash layer at the lower 10-15 mm of bed; base surge laminae and layer containing rounded scoriaceous clasts, some with fine ash armour; sharp gradation from coarse lithic clasts below to fine ash accretionary lapilli layer with some armoured lapilli

B: fine ash layer with occasional accretionary lapilli (identifiable where weathered out) and lithics; wavy bedding formed from impacting material in bed above; coarse lithics; mainly fine ash bed containing accretionary lapilli: some have coarse particle weathering out of core; lithic material has impacted into the top of the layer

Lower Footprints Ash layer: thick massive fine ash bed containing at least two accretionary lapilli horizons directly below major unconformity (McPhie et al., 1990)

A: accretionary lapilli horizon approx. 4.5 cm thick; accretionary lapilli horizon approx. 2 cm thick

Fig. 2 Upper proximal section, Sandhill gullies (about 1 km SW of Halemaumau)

The deposits from this eruption consist mainly of coarse pyroclastic beds and finely laminated base surge strata that form dunes in proximal areas, and thin with distance away from the vent. Erosional gullies cut through the deposit at Sand Hill, about 1 km southwest of Halemaumau Crater, and expose an almost complete proximal section (Fig. 2).

Several accretionary lapilli horizons were identified and characterised based on accretionary lapilli morphology and size. The layers could be traced along numerous gullies in a SW direction, along the dispersal axis of the deposit to more distal areas.

Sandhill gullies are fault-bounded fluvial erosional features

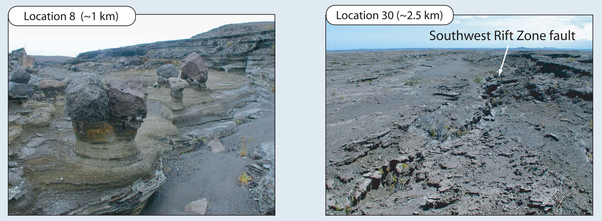


Fig. 3 Sandhill gullies: Loc. 8 about 1 km SW of Halemaumau and Loc. 30 about 2.5 km away, the extent of base surge deposits

Field evidence suggests that these features are formed by fluvial erosion and follow faulting in lava flows at the base of the Keanakak'oi Ash. Fig. 3 shows the gullies in a proximal area about 1 km SW of the Summit Caldera (loc 8) where water erosion has left tuff stacks supporting boulders. The extent of the gullies was at about 2.5 km (loc 30), and tuff deposits here are largely eroded down to the basal lava flow, exposing large SW trending faults related to the rift zone.

Accretionary lapilli layers: powerful tools in stratigraphic correlation

The accretionary lapilli beds can be traced away from Sand Hill and correlated to these more distal deposits through identification of unique characteristics and small-scale stratigraphic relationships.

Fig. 4 shows an example of the features identified and used to map two accretionary lapilli layers at the top of the section. The upper of these forms impacts sags into massive ash at the base of the layer and has a thickness of ~40 mm in proximal sections. The lower has a high proportion of armoured lapilli and a thickness of ~20 mm. The two are separated by cross-stratified base surge beds.

These two beds were easily identified from their distinctive characteristics, and could be followed from exposures at Sandhill out into the desert.

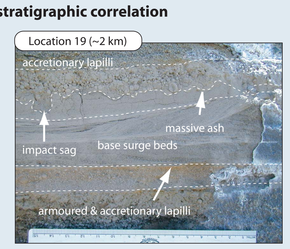


Fig. 4 Accretionary lapilli beds at top of section: micro-stratigraphical characteristics used to identify beds

Wash-pan area SW of Sandhill gullies: medial between proximal & distal deposits

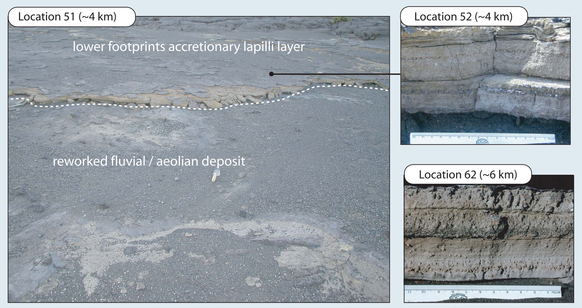
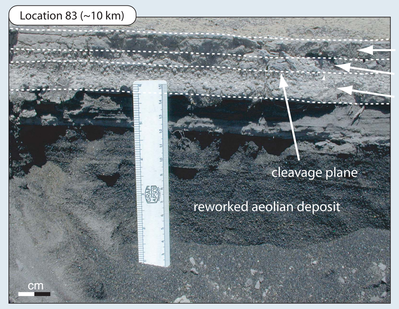


Fig. 5 Sandhill gullies: Loc. 8 ~1 km SW of Halemaumau and Loc. 30 ~2.5 km away, the extent of base surge deposits

Footprints accretionary lapilli layers



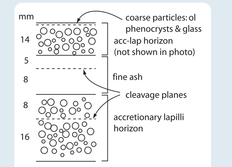


Fig. 6A Lower Footprints ash layer, at 'Footprints' location

Location 51 (Fig. 5) exceeds the run-out distance of base surge and pyroclastic flows from the Keanakak'oi Ash eruptions. There are two types of deposit here: surge and flow fine ash fallout (containing accretionary lapilli) and reworked fluvial / aeolian sands composed of coarse to fine glassy ash deposited mainly as run-out from Sandhill gullies. Two massive fine ash layers are exposed at this location: the upper of these two layers resembles the lower footprints accretionary lapilli layer in terms of micro-stratigraphy, accretionary lapilli occurrence and thickness (see Fig. 6A). At location 62 (Fig. 5), the layer was preserved in the lee of a small tumulus depression that protected it from erosion. It is composed of several horizons, separated by cleavage planes along which the sample easily divides. Fig. 6C shows the LFP acc-lap size distribution at several locations.

Upper and Lower footprints accretionary lapilli layer separated by erosional unconformity

The Lower Footprints ash (LFP) layer (Fig. 6A) is separated from the Upper Footprints ash layer (UFP) by an erosional unconformity (Fig. 6B) and therefore, must be older than 1790, the estimated date of the last major explosive eruption of the Keanakak'oi ash (excluding Halemaumau in 1924). Dune sand (Malin & Krinsley, 1980) separates the two layers in most places, reaching a maximum thickness of about 1-2 m. However, at location 81 (Fig. 6B) the ash layers are in contact where wind has eroded the dune deposits away completely. This represents a significant depositional hiatus between the UFP and LFP to allow for the build up and subsequent erosion (in places) of aeolian dune sand. The unconformity corresponds to the one observed at location 7 (Fig. 2) and places the LFP in the Middle Keanakak'oi Ash (McPhie et al. 1990).

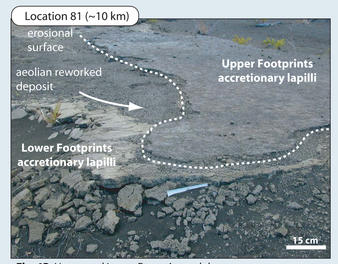


Fig. 6B Upper and Lower Footprints ash layers

Conclusions

The Footprints accretionary lapilli layers (Upper and Lower) are separated by an erosional unconformity at a location 10 km along the dispersal axis of the deposit: up to 1-2 m of aeolian deposits are present between in places, representing a significant depositional hiatus. The Lower Footprints layer therefore must be older than 1790, the date of the last major explosive event in the history of the Keanakak'oi Ash (not including Halemaumau in 1924).

The Lower Footprints accretionary lapilli layer can be followed from more distal areas, across the Kau Desert, to proximal sections exposed along Sandhill gullies: the LFP is placed below a major unconformity recognised by McPhie et al. (1990), within the uppermost 1-2 m of the section.

Field observations suggest that Sandhill gullies are fluvial erosional features that follow major faulting related to the Southwest Rift Zone.

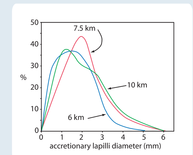


Fig. 6C Acc-lap size dist. of LFP layer

Structural characteristics of Keanakak'oi acc-laps: evidence for freezing (or dessication)?

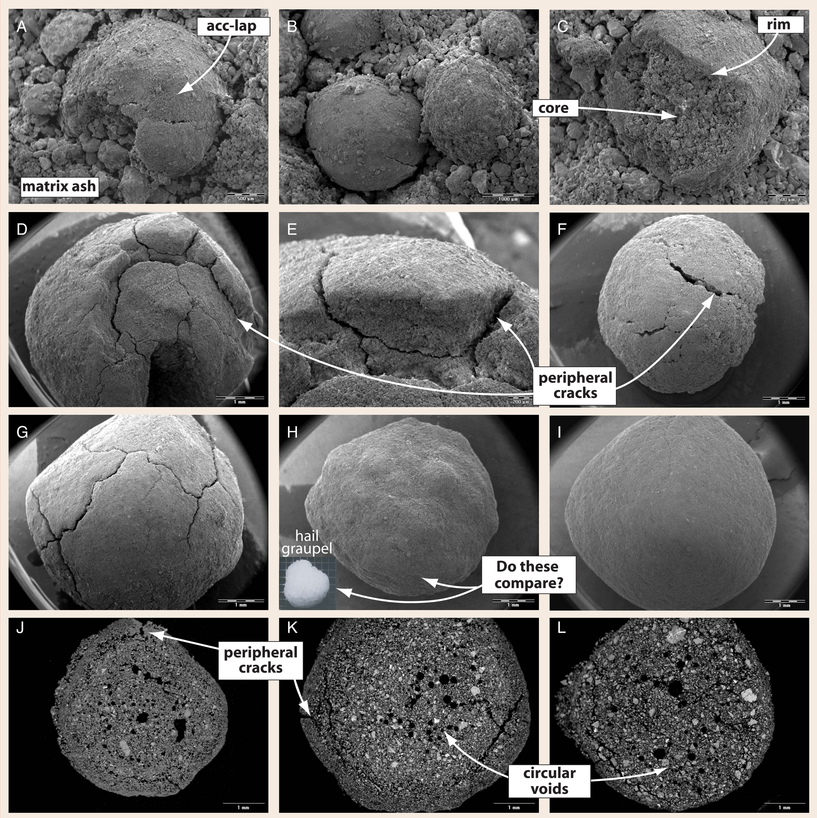


*Fig. 7 Scanning Electron Microscope images of Keanakak'oi accretionary lapilli. **A-C** Secondary Electron (SE) images of accretionary lapilli in situ, illustrating finer-grained aggregate present in coarser matrix. **D-I** SE images showing variation in aggregate morphology and peripheral cracking observed in many examples. **J-L** Back-Scattered (BS) images of cross-sections through the accretionary lapilli, illustrating areas of circular voids.*

Peripheral cracking (A-G; J-L)

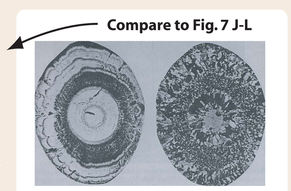
Many of the accretionary lapilli examined displayed some kind of cracking, mainly around the periphery of the aggregate, observable in both BS and Secondary Electron (SE) mode. In some examples, fractures disect the concentric structure and segregate an area of the outer core and rim from the core. Other fractures following the concentricity of the structure were also observed within the core region.

Circular void spaces (J-L)

Cross-sections in Back-Scattered (BS) mode reveal a coarse-grained core region that occupies the majority of the diameter of the aggregate, enclosed by a finer-grained rim of a few hundred microns thickness. All except for 2 (out of 16) accretionary lapilli contained circular void spaces in the core region. There were numerous circular voids in some of the larger aggregates measuring, in most cases between 100-300 µm diameter, with a few reaching over 500µm (significantly larger than enclosing ash particles). These large voids were concentrated towards to centre of the aggregate. Also observed in the majority of cross sections was a region of increased void space composed of small circular voids (generally <100 µm) with diameters of the order of surrounding particles, in the outer core. At least two of the cross-sections examined contained a smaller accretionary lapilli inside the core of a larger one. Present immediately outside of the smaller accretionary lapilli was a region containing many circular voids.

Air bubbles in hailstones

It has been shown experimentally in hailstone formation that air dissolved in water can be liberated by an advancing ice-water interface and form bubbles (Murray and List 1972; List et al., 1973). Additionally, in a certain type of hailstone growth, environmental air can also be trapped between accreted water droplets and form bubbles. In the case of hailstones, the study of air bubble size distributions and concentrations may be used for interpretation of the growth history. The main factor that affects the mean air bubble size and number is liquid water content, with temperature variations having a secondary effect (List & Agnew 1973).



Thin sections of hailstone under normal transmitted light on left & polarised transmitted light on right (from Pruppacher & Klett 1997).

Circular voids in accretionary lapilli analogous to air bubbles in hailstones?

The circular voids are interpreted to be spaces in the aggregate structure once occupied by spherical air bubbles. It is unlikely that water occupied these spaces during the formation of the aggregate, as the whole core would have been homogeneously 'wet'. It is also unlikely that these features formed from accretion of ice crystals which melted on deposition leaving behind a void, based on morphology (Cantrell, personal comm.). Fracturing observed in the accretionary lapilli structure also has analogies with hailstone structure in freezing experiments where growth proceeded through the formation of spongy ice (~-5 to -15 C) (List & Agnew, 1973): cracking was observed during cooling after the experiments as the temperature fell below -15 C.

Dessication?

It is conceivable that these features (i.e. cracking and circular voids) may have formed as the aggregate and containing ash layer dried out in the hot desert sun. Water inside the aggregates would evaporate and migrate into pockets inside the core, with the potential to form small voids. However, it is unlikely that these would form such circular features in cross-section, and certainly not on a scale larger than enclosing particles. Shrinkage resulting from dessication could also form cracks. Dessication cracks were observed throughout the Footprints acretionary lapilli ash layers. However, cracks originating in the aggregates were constrained there, and did not migrate into the enclosing matrix (Fig. 7 A-C), suggesting these features formed pre-deposition. It is possible that some collisions between aggregates during deposition may result in structural deformation (e.g. Fig. 7 F), but on the whole, these cracks are interpreted to be a result of expansion of the core as it froze in the atmosphere, prior to deposition (from the increase in volume associated with the phase change from water to ice). Continued freezing (as the process would not be instantaneous) may enable cracks to propagate and penetrate the rim, after that formed.

Conclusions

Circular voids and cracking observed in the structure of aggregates from the Keanakak'oi Ash may be analogous to similar structures seen in hailstones: this would imply ice is involved in the aggregation process. Cracking is not interpreted to be a result of dessication: cracks observed in aggregates do not propagate into the matrix, suggesting a these features are formed by a process unique to the aggregates.

Grainsize characteristics of Keanakak'oi accretionary lapilli: base surge origin

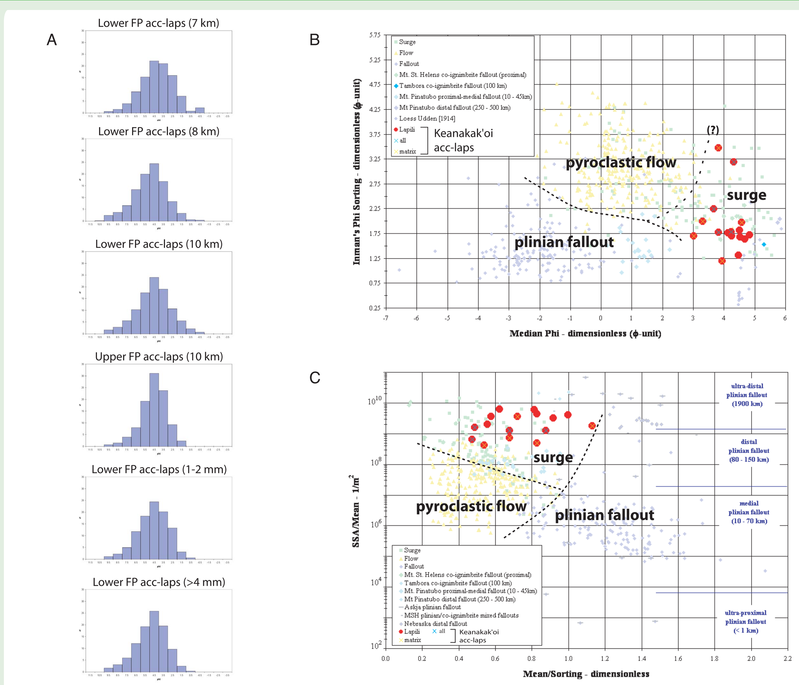


*Fig. 8 Grainsize distributions (GSD) of ash particles comprising Keanakak'oi accretionary lapilli. **A** Phi charts illustrating GSD of accretionary lapilli from UFP and LFP accretionary lapilli-bearing ash layers, and of different sized accretionary lapilli. **B** GSD of Keanakak'oi accretionary lapilli plotted on a traditional grainsize chart of Inman's Phi sorting versus median Phi. Several other datasets constrained by eruptive style have been plotted for comparison (data from Dartevelle et al., 2002). **C** Same data as in B plotted on SSA mean versus mean sorting chart.*

Grainsize distribution of individual accretionary lapilli

The aim of this part of the study was to see if there is any variation in the grainsize characteristics of the accretionary lapilli-bearing layers of the Keanakak'oi Ash with increasing distance from the approximate location of the vent at Halemaumau crater. Individual aggregates were removed from surrounding matrix in samples collected at distances of 7, 8 and 10 km along the dispersal axis of the deposit. These were disaggregated and grain size analysis was carried out using a Microtrac particle size analyser.

The GSD of these analyses is displayed in Fig. 8A as Phi plot frequency distributions. It can be seen that regardless of distance from source, layer sampled and accretionary lapilli diameter, all GSD have the same mode at Phi 4.5. There is a very slight variation in sorting between the two Footprints layers, with the upper being slightly more well sorted. However, the shape of all of the distributions is very similar, suggesting the underlying aggregation process is independent and ubiquitous.

Characterisation of Keanakak'oi Footprints accretionary lapilli layers using grainsize distributions

Grainsize distributions were determined for components of accretionary lapilli-bearing tuff layers of the Keanakak'oi Ash, including individual accretionary lapilli, matrix ash and complete horizons. When plotted on specific surface area (SSA) mean versus mean sorting chart (Fig. 8C), all components fell within the region characterised by co-ignimbrite plume fallout, in this case originating from a base surge. This relationship is more ambiguous when plotted on the more traditional Phi sorting versus median Phi chart (Fig. 8B).

These graphs imply that the characteristics of the ash particles comprising the aggregates, and indeed the whole accretionary lapilli layers, are similar to fine ash fallout from co-ignimbrite plumes, specifically to ash sampled from base surges. It can be seen from Fig. 8C that the ash contained within the individual aggregates (found at distances of less than 10 km from the vent) compares to distal plinian fallout normally sampled at distances greater than 100 km where there has been no aggregation. This gives support to the idea that aggregation will cause the premature settling of fine ash.

Conclusions

GSD modes for ash comprising accretionary lapilli from the Footprints layers of the Keanakak'oi Ash are the same at Phi 4.5, independent of distance from source, layer sampled and accretionary lapilli diameter.

The particle characteristics of ash composing accretionary lapilli sampled resembles the host layer: the beds sampled all displayed field relationships suggesting that these were fallout from surges, which was reflected in analysis of the grainsize characteristics (Fig. 8C).

It may be possible to use the grainsize characteristics of ash deposits to accurately determine the origin, based on a recent study by Dartevelle et al. (2002).

Future work

More accretionary lapilli-bearing layers need to be analysed from other volcanoes to increase the grain size dataset for ash aggregates. This will then allow for a more well-constrained interpretation of aggregation processes.

References and Acknowledgements

Dartevelle, S., Ernst, G.G.J., Stix, J. & Bernard, A. (2002) Origin of the Mount Pinatubo climactic eruption cloud; implications for volcanic hazards and atmospheric impacts. Geology 30 (7):663-666
Jaggar, T.J. (1930) The human footprints in Kilauea's ash bed. Volc Lett 273:1-3
List, R. & Agnew, T.A. (1973) Air bubbles in artificial hailstones. Journ Atmos Sci 30:1158-1165
List, R., Murray, W.A. & Dyck, C. (1973) Air bubbles in hailstones. Journ Atmos Sci 29:916-920
McPhie, J., Walker, G.P.L., & Christiansen, R.L. (1990) Phreatomagmatic and phreatic fall and surge deposits at Kilauea volcano, Hawaii, 1790 A.D.: Keanakakoi Ash Member. Bull Volcanol 52:334-354
Malin, M.C. & Krinsley, D. (1980) Bedded sands within the Keanakak'oi Formation near Mauna Iki, Hawaii: aeolian or base surge deposits? Tempe, A.Z., Arizona State University, unpublished ms., 16 p.
Murray, W.A. & List, R. (1972) Freezing of water drops freely suspended in a vertical wind tunnel. Journ Glaciology 11:415-429
Pruppacher, H.R. & Klett, J.D. (1997) Microphysics of clouds and precipitation. Kluwer Academic Publishers, London
Westervelt, W.D. (1966) Hawaiian Legends of Volcanoes. 3rd edition, Charles E. Tuttle Co., Japan, pp. 139-145

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