Whitneys Cave, an Old Mauna Loa/Hawaiian Pyroduct below Pahala Ash: An Example of Upward-Enlargement by Hot Breakdown

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Abstract

Exploration and survey of Whitneys Cave has yielded astonishing insights into the processes that act to enlarge the tunnels of underground lava conduits. The current cave entrance is a cold puka (breakdown hole) situated below the Ninole Hills that represent the oldest exposed Mauna Loa lavas, possibly several hundreds of thousand of years old. The cave occurs in the slightly rolling, inclined plain below the Ninole escarpment. This plain was formed by Mauna Loa flows that came down the Ninole Hills. The plain is covered by several meters of Pahala Ash but this is not a well-defined stratigraphic unit and may represent ashes of various, albeit pre-Holocene ages. In the area of investigation it is assumed to belong to the unit “k” of the Mauna Loa Kau-Basalts, which includes the basalt of the cave. A published 14C date for a k-basalt flow near Nahalehu is 31,100 ± 900 a. This suggests that Whitneys Cave is one of the oldest yet-described caves on Mauna Loa. Another k-basalt cave is the Kamakalepo / Waipouli System. On Hawai‘i only the Pa‘auhau Civil Defense Cave, a pyroduct of the Hamakua Series of Mauna Kea is older.

Considering the fact that the cave does not show rapid alterations in slope, the smallest cross-sections provide “valves” regulating the maximal possible lava transport and suggesting that the larger sections of the cave could never have been filled entirely with lava. This conclusion is substantiated by the observation that the cave shows throughout its length glazed linings that are not much higher than 1 m.

In consequence, the larger halls must have been created by erosional processes, acting during the activity of the lava flow. We know of two such processes: downcutting and upward growth by breakdown. In the case of Whitneys Cave the latter process seems to have dominated. The cave must have experienced a considerable upward (and sideward) enlargement by breakdown of blocks. Roff sheets are quite thick and have generated blocks weighing tons that are now missing. Consequently, these blocks were removed through the comparatively small “valves”, but without clogging the conduit. This leads to the much-debated possibility of remelting. It costs a large amount of energy to melt basaltic rocks once crystallized. In the case of Whitneys Cave however, evidence shows that the roof (both the inflation-generated primary roof and the secondary cover of surface pāhoehoe sheets) was still hot and that the blocks generated from it did not need to be heated from ambient surface temperature but could still have temperatures of above 800°C, thus saving a considerable amount of energy in the remelting process. It is interesting that the removal of the blocks must have been quite efficient, since only a few lava balls (coated fragments of breakdown) have been noticed throughout the cave.

Introduction

Post-eruptional lava flow downhill is a process that affects large areas. Yet text books do not particularly focus on this chapter of volcanism. Lava can flow across the surface in several forms, governed by viscosity. It in turn is a function of temperature, chemistry, phenocryst concentration, gas content, temperature and slope. High temperature basaltic lavas tend to flow in one of two forms: A‘a and pāhoehoe (compare Lockwood, 2010). A‘a flows can best be compared to glaciers, i.e. they move with almost their entire mass. At the front the rubble riding the surface is dumped and overrun, forming a bottom bed of loose or welded clasts. The whole process is reminiscent of the movement of the chains of a bulldozer. At the sides rubble is dumped as well, often forming sort of side “moraines”. Pāhoehoe flows on the other hand tend to form channels with fast running interiors or build lava conduits that hide the flowing lava from view. This “self-insulation” of the flow enables these lavas to flow down very low slopes (often <1°) and across very long distances. Thus the lava flow deposited as pāhoehoe is stationary because the lava moves only through a central conduit, depositing new lava at the distal end of the flow. Since the lava extruded there is very hot and fluid, it forms a lava delta of a thin sheet, cooling rapidly. Gas quickly exsolves and the overall rock density is diminished by vesicle formation. The next pulse of lava will therefore lift this layer up, a process called “inflation” (Hon *et al.* 1994; Kempe 2002). Thereby many sheets of lava can be deposited, with the top one being the oldest and the lowest one the youngest in the series. Once temperature in the inside of the stack remains high enough the conduit is extended and a new series of advances and inflation is initiated. Thus a tunnel conducting molten lava is established, originally termed a pyroduct (Coan 1844; Lockwood 2010) but also known as lava tunnel or tube. This internal conduit is often active for weeks or months and can erode, thereby creating a tunnel in which the lava flows like a river in a canyon-like cave. Erosion and enlargement and the processes of lava transport inside of the pāhoehoe flows can therefore not be studied directly but vulcanospeleological studies can illustrate some of these processes that occur during the activity of the flow.

Geological situation

Exploration and survey of Whitneys Cave[1] by the authors in March 2010 yielded astonishing insights into the processes that act to enlarge the tunnels of underground lava conduits. The current cave entrance was kindly shown to us by the owner of the property, Mr. Whitney Cossman. It is situated below the Ninole Hills that represents the oldest exposed Mauna Loa lavas, possibly several hundreds of thousand of years old (e.g. Wolfe & Morris 2001) (Fig. 1). Whitneys Cave occurs in the slightly rolling, inclined plain below the Ninole escarpment, formerly used by the sugarcane industry and now replanted with Macadamia Nut trees (Fig. 2). This plain was formed by Mauna Loa flows that came down the Ninole Hills delivered by eruptions of the Mauna Loa SW-Rift in prehistoric times. The plain is covered by several meters of Pahala Ash. However, "Pahala Ash" is not a well-defined stratigraphic unit and may represent ashes of various, albeit pre-Holocene ages (e.g., Wolfe & Morris 2001 p. 15). In the area of investigation it is assumed to belong to the unit "k" of the Mauna Loa Kau-Basalts, which includes the basalt of the cave. Lipman & Swenson (1984) published a ^{14}C date for a k-basalt flow near Nahalehu of 31,100 ± 900 aBP. This date suggests that Whitneys Cave belongs to one of the oldest yet-described flows on Mauna Loa. Another k-basalt cave is the Kamakalepo/Waipouli System analysed by Kempe *et al.* (2008a, b and 2009). On Hawai'i only the Pa'auhau Civil Defense Cave, a pyroduct of the Hamakua Series of Mauna Kea, is older (Kempe *et al.* 2003).

Topography of the cave

The cave entrance is a "puka" - a cold breakdown hole - puncturing the ceiling of the cave as well as the Pahala Ash that is 3 m thick here. From this puka the shorter downslope (makai) and the longer upslope (mauka) sections of the cave are accessible (Fig. 3a,b,c). The makai section was extended by a dig along one wall of the cave through ash and breakdown (St. 70-72) (Fig. 4). The ash is part of the fill of a larger puka extending from station 26 to 72 containing ash, blocks and garbage (glass bottles, china fragments). The makai passage ends at the fill of yet another puka (St. 80). The mauka section is not only much longer but also wider and higher than the makai section. In parts

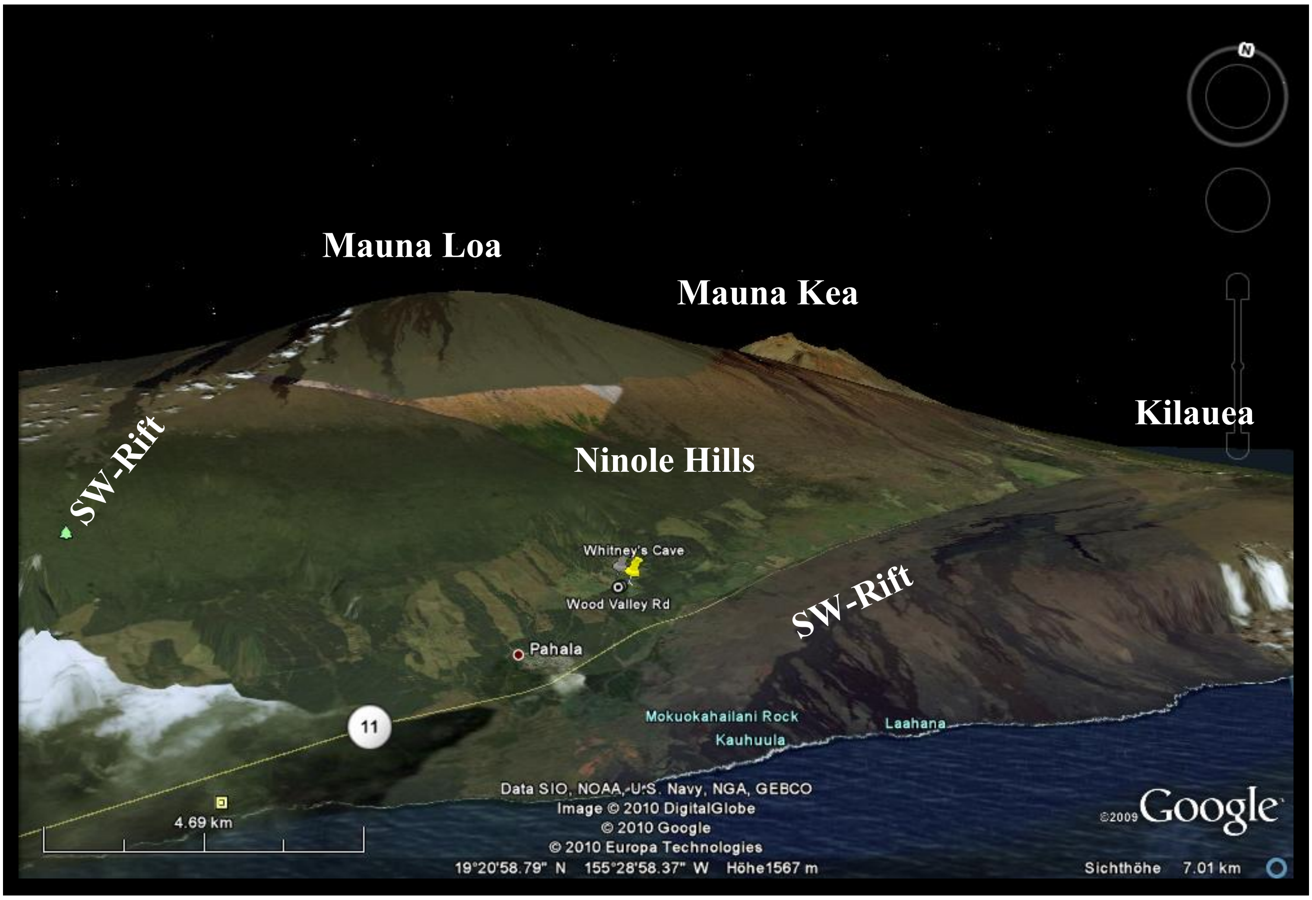

Fig. 1. General situation of Whitneys Cave on the SW Flank of Mauna Loa, Hawaii (Google Earth image).

[1] Also dubbed Whitneys Dolphin Cave because of a dolphin-like lava ball at Station 46.

Fig. 2. Trace of Whitneys Cave below former sugar cane country. Note puka mauka of Whitneys Cave that served as a sink for water from sugar cane fields and that might mark a former upper entrance to the cave (Google Earth image).

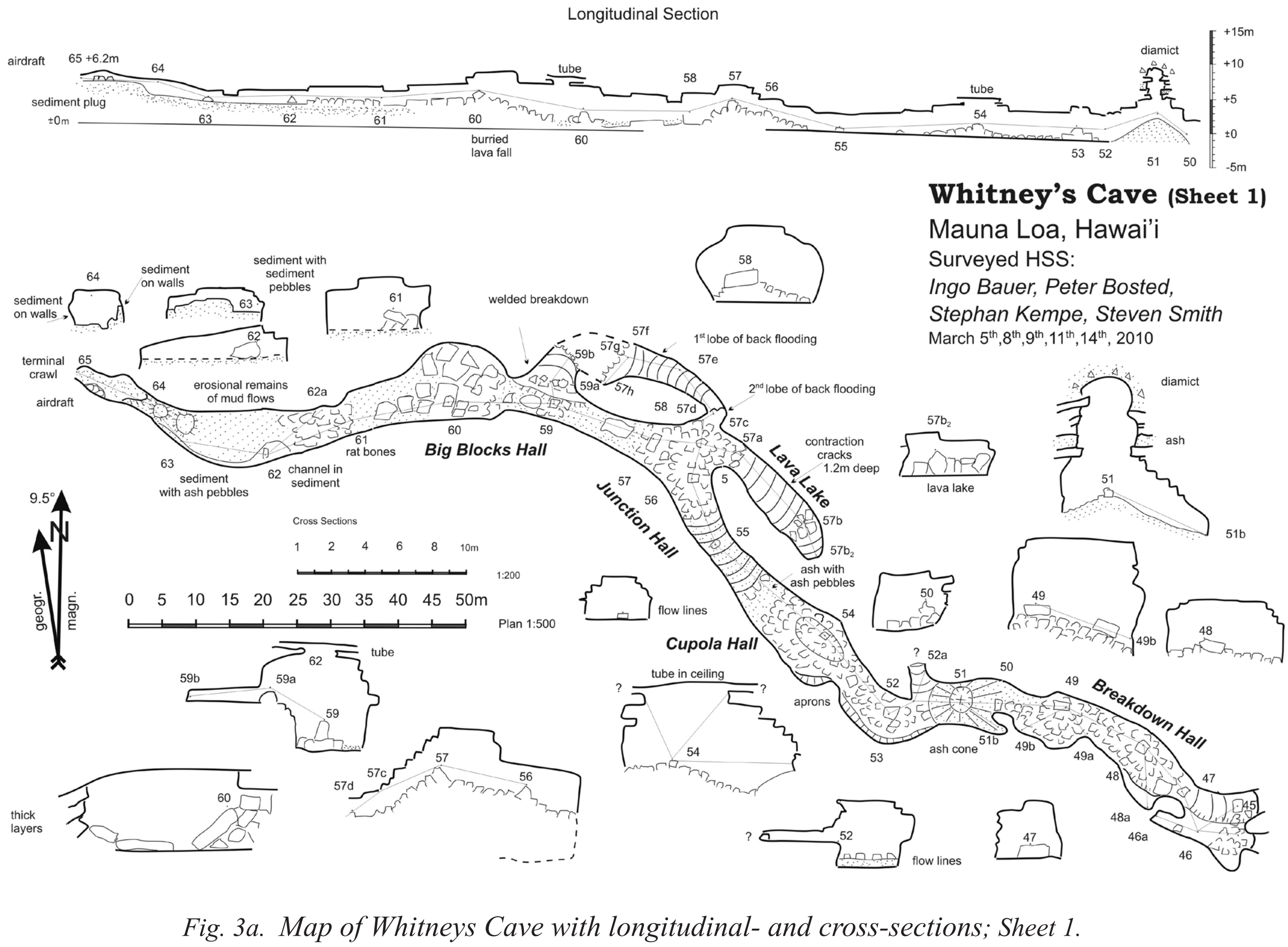

Fig. 3a. Map of Whitneys Cave with longitudinal- and cross-sections; Sheet 1.

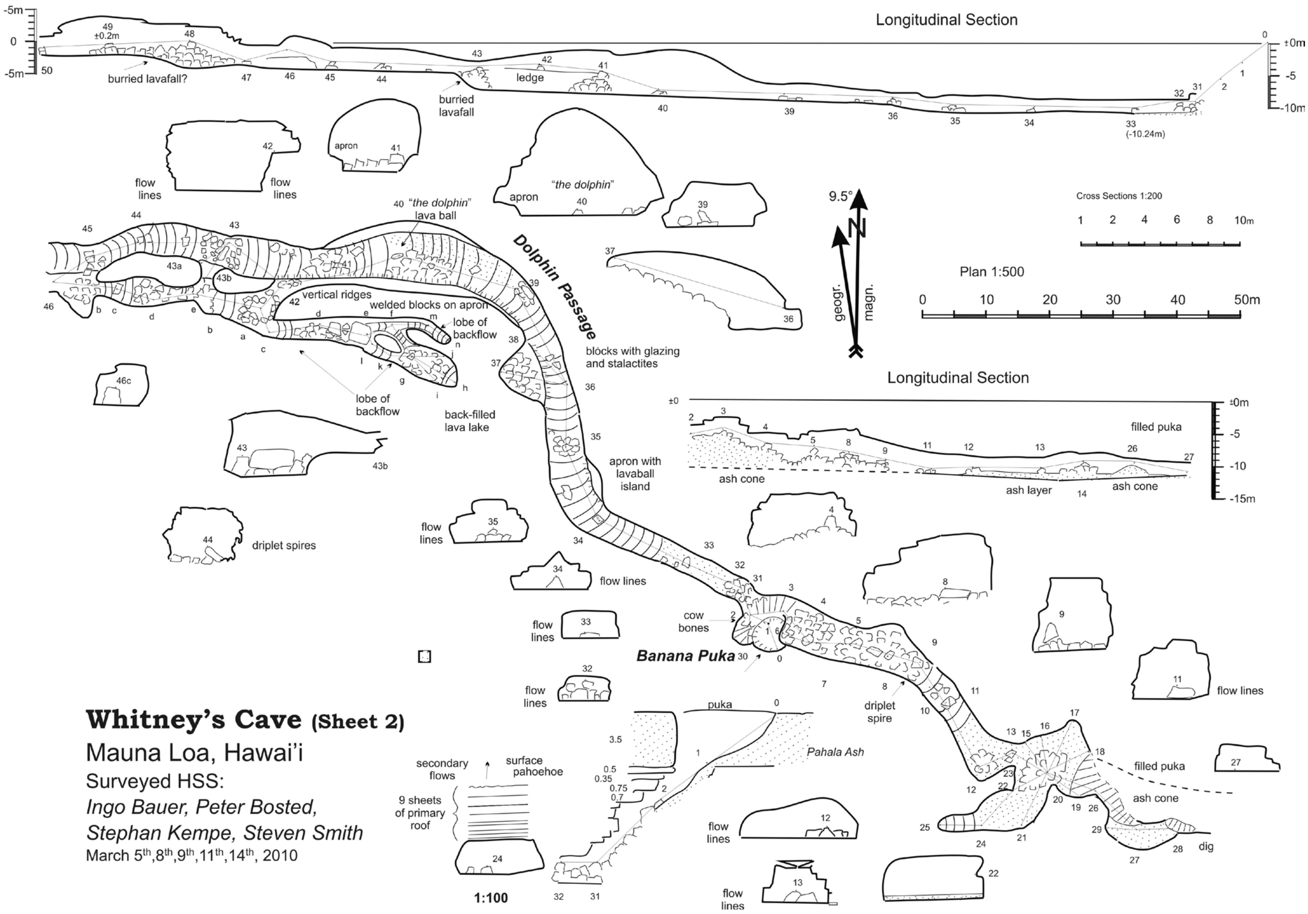

Fig. 3b. Map of Whitneys Cave, with longitudinal- and cross-sections; Sheet 2.

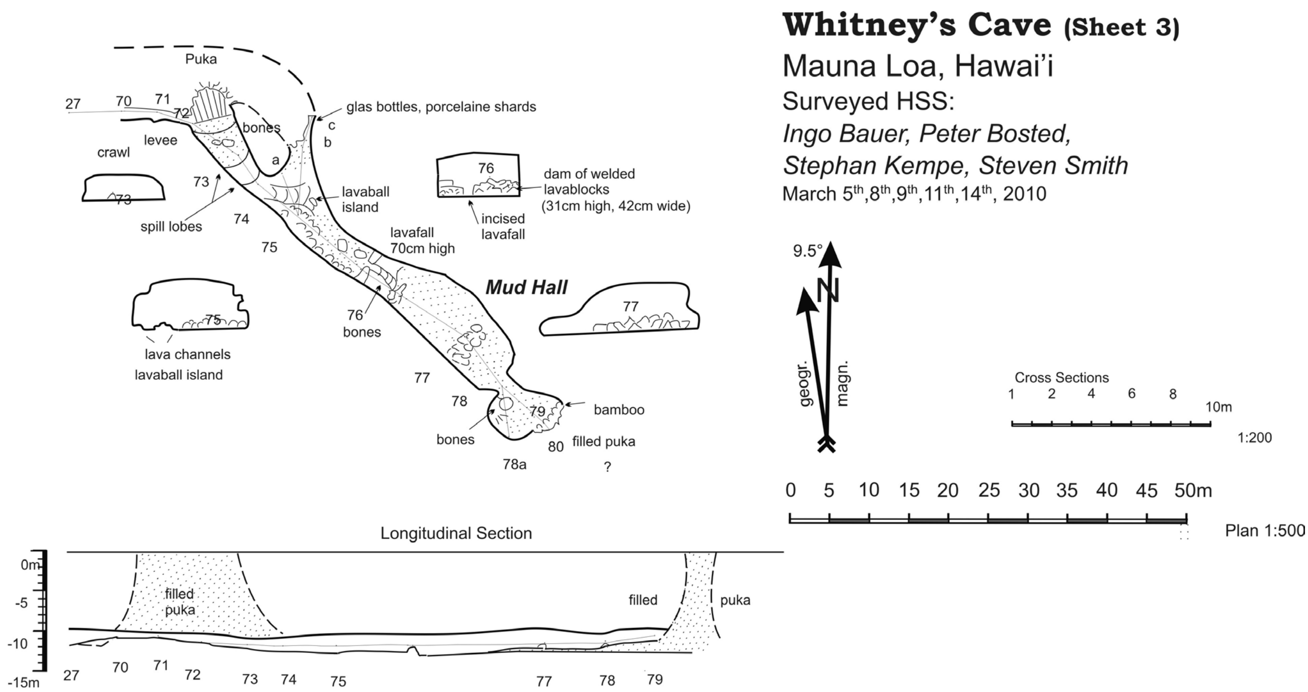

Fig. 3c. Map of Whitneys Cave, with longitudinal- and cross-sections; Sheet 3.

substantial breakdown occurred, throwing big, up to 3 m long pāhoehoe slabs to the floor of the cave (Fig. 5). Where the original floor is visible it is composed of rough pāhoehoe often sharp-edged like a‘a rubble. In many parts sediment (washed-in ashes) covers the floor thinly. Towards the mauka end, these also contain rounded pebbles of consolidated dark red ash (Fig. 6) and small fragments of rock, transported by water into the cave. The mauka end of the cave is filled with a 1.5 m thick body of sediment (Fig. 7), possibly a mud flow containing larger pebbles and lithic fragments. It is now eroded by water, washing the finer particles further downslope. Here also bushy, mauka-directed coralline (possibly calcite) mineral speleothems occur

Fig. 4. Dig along the flank of a sediment cone filling a puka to open the lower section of Whitneys Cave.

Fig. 5. Upper section of Whitneys Cave with very large (for lava caves) breakdown blocks.

Fig. 6. Rounded pebbles of an ash deposit washed into the upper end of cave (note tape case for scale)

Fig. 7. Sediment plug of the upper end of Whitneys Cave.

Fig. 8. Calcite (?) bushes at the mauka end of Whitneys Cave, indicating (former ?) airflow.

(Fig. 8). At the end a draft is felt from fractures in the pāhoehoe. The cave points towards a puka, noticed about 200 m uphill at a road fork (see Fig. 2). Into it the sugar plantation had directed its runoff from a large sugarcane field, thus explaining the encountered fill of the cave at its terminal end.

Table 1 lists the main survey results. Main trunk length (horizontal) is 502 m and total length is 643 m (which is variable depending on which sections of side passage shots are included). At Station 31 the floor of the cave is reached at 10.7 m below the surface. The deepest point is 13.5 m below the entrance at St. 76, and the highest point of the floor is at the mauka

Table 1 Main survey results (March 2010) of Whitneys Cave (magnetic declination 2010 Hawaii = 9.5° E).*

Length with side passages	real (m)	horizontal (m)	
Makai	190.22	188.88	
Mauka	461.43	454.02	
Total	651.65	642.9	
Main trunk length	real (m)	horizontal (m)	Vertical (m)
Makai St. 2-80	154.47	153.23	-5.75
Mauka St. 2-65	355.04	349.06	11.51
Total	509.51	502.29	17.26
Extension	W-E (m)	S-N (m)	“beeline” (m)
Makai	121.26	72.16	141.1
Mauka	274.06	118.02	298.39
Total	395.32	190.18	438.68
Directions	mag N.(°)	geogr. N.(°)*	
Makai	300.75	291.25	
Mauka	293.3	283.8	
Sinuosity	1.145		
Slope	1.97°		

end of the cave which is 6.21 m above the surface at the entrance. Concatenation of the entire main trunk survey line yields a vertical difference of 17.3 m (both end points are on ash fills and are similarly high above the real floor of the cave). This yields a general slope of the cave of ($\tan^{-1}$ 17.26/502.29) of 1.97°. The sinuosity calculated by dividing the main horizontal trunk length by the "beeline" (distance between the mauka and makai endpoints of the cave) yields 1.145. Both slope and sinuosity are comparable with other caves mapped on Hawaii (compare Kempe 2009, Table 1).

Table 2 lists the average heights and widths for Whitneys Cave. Heights and widths are the sums of the up and down and right and left measurements recorded at the stations along the main trunk passage. Because not all stations are in or near the centre of the passage, the height data may be smaller than the actual largest height of the passage while the width measurements are more closely representing actual widths. Also height is modified by various layers of ash fills, reducing the actual height of the passage. Nevertheless the data illustrate a substantial variation along the course of the main passage of the cave. In general the cave is much wider in the mauka section than in the makai section. It is widest at St. 60 (11.2 m) but widths of more than 10 m are also reached at stations 57 and 54. Overall the height (mean 3.22 m) shows more variation than the width (mean 5.64 m). The minimal width listed in the Table 2 is for Station 74 and is that of a side passage (main passage closed because of collapse and later filling from the surface), so that the minimal width of the main passage is found at station 64 (one station below the ash-filled mauka end = 2.8 m) and at Station 31, 32 (3.3 and 3.0 m, resp.). At these stations also the ceiling height is not very large (1.9, 2.0 and 1.5 m, resp.). Since at these stations the cross-sections are more or less square, the minimal passage cross-sections amount to 5.3, 6.6 and 4.4 m^2 (in fact these are upper values since the passages are not exactly square). In contrast to this the largest cross-sections are something in the order of 50, 40 and 30 m^2 for those stations mentioned above with the largest widths. Considering the fact that the cave does not show rapid alterations in slope (the survey lines do show considerable ups and downs, but this is mostly caused by the necessity to overcome breakdown piles) the smallest cross-sections provide "valves" regulating the maximal possible lava transport and suggesting that the larger sections of the cave could never have been filled entirely with lava. This conclusion is substantiated by the observation that the cave shows throughout its length glazed linings that are not much higher than 1 m (Fig. 9).

Table 2. Average heights and widths of Whitneys Cave, for heights Stations 51 (cupola into Pahala Ash), 26 (ash cone) and 70 and 71 (dig stations) were taken out of the calculation and for widths stations 14 (hall) 26 (ash cone) and 70 and 71 (dig stations) were left out.

Value	Height (m)	Width (m)
Max	6.75	11.17
Min	1.01	2.65
Mean	3.22	5.64
Stand. Dev.	1.46	2.12
Coef. Of Var	45.3%	37.6%

Fig. 9. Levee in the hall of station 14, showing that the lava was never standing more than about 80 cm high. The cavity above it must have been created by breakdown.

Erosion by breakdown

In consequence, the larger halls must have been created by erosional processes, acting during the activity of the lava flow. We know of two such processes: downcutting and upward growth by breakdown (e.g. Allred & Allred 1997; Kempe 1997, 2002, 2009). In the case of Whitneys Cave the latter process seems to have dominated.

The evidence comes from three lines of observations:

Downcutting is very often associated with backcutting lava falls. In Whitneys Cave only one small lava fall is visible (at Station 76; it cut through a dam of welded breakdown in the final phase of activity and has a height of only 0.4 m). There may be two more, but buried under breakdown at Station 43 and between 49 and 47. Backcutting lava falls created plunge pool rooms that typically have a large width mauka and taper out makai. This pattern is not seen on the map of Whitneys Cave. Downward erosion also drains the side passages, leaving them high above the final floor. In Whitneys Cave the differences between the floors of the side passages and that of the main passage is small. At station 52, where a side passage joins the main passage, it is in the order of 1.2 m which is probably a good measure of how much the main passage has actually cut down. This small amount of downcutting cannot explain the generation of the large halls.

Upward enlargement on the other hand by breakdown can only become a major process if the roof of the cave is thick enough. Whitneys Cave appears to have been created by the process of inflation (Hon *et al.* 1994). During this process (Kempe 2002, 2009) a stack of pāhoehoe sheets is created, with the oldest on top (having the typical ropy surface morphology) and the younger sheets below (having shear plane contacts). This structure of the primary roof is seen at several places, best at Station 25 (Fig. 10) where the primary roof has nine layers, between 6 and 44 cm thick, and ends 2.7 m above the floor of the side passage entering

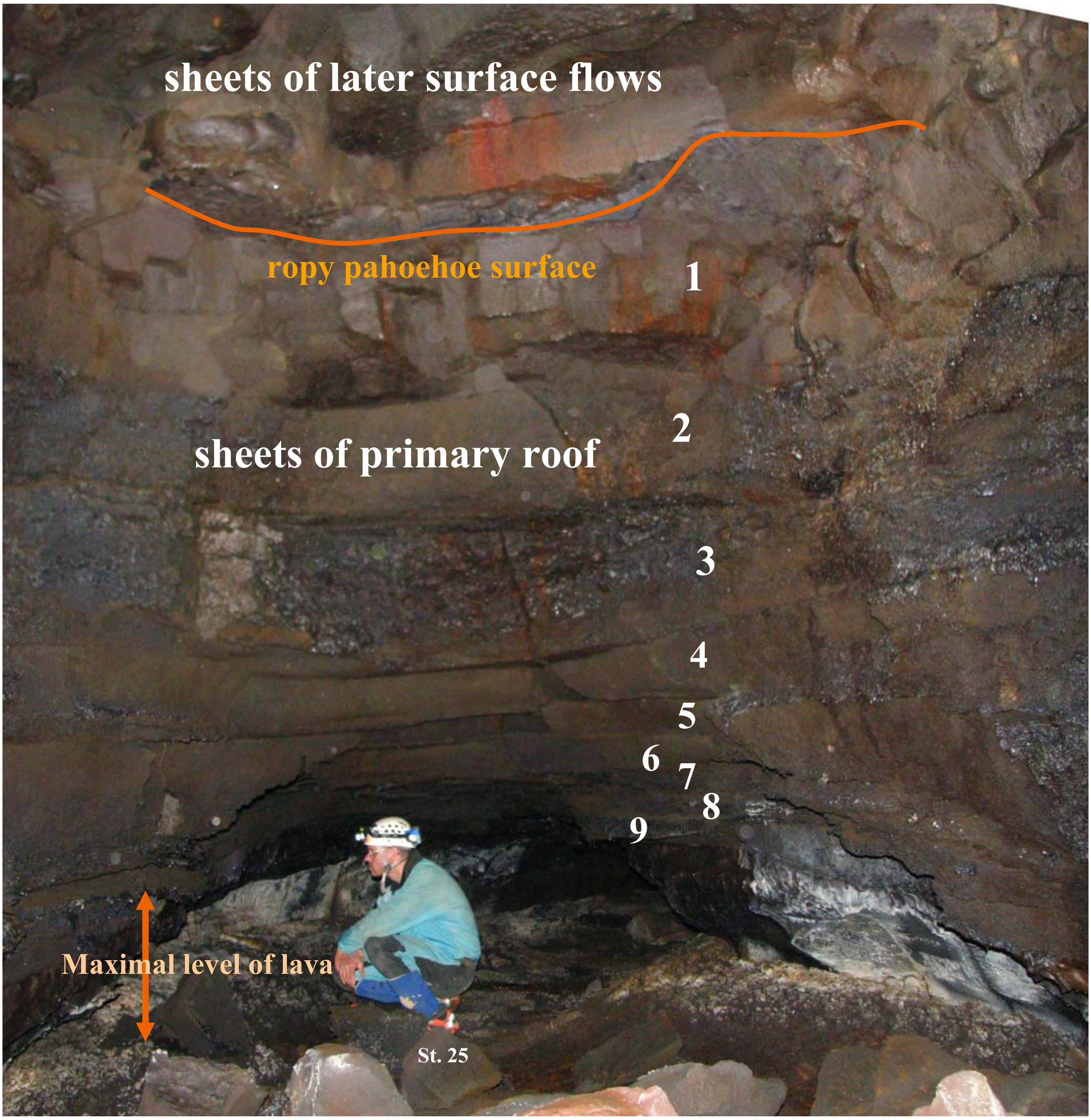

Fig. 10. View mauka from Station 24 with the nine inflationary sheets composing the 2.7 m thick primary roof. Sheet No. 1 is the oldest, carrying pāhoehoe ropes at its surface. The layers decrease in thickness toward the bottom because the upper inflationary layers were less hot when emplaced. Layers above sheet 1 were secondarily placed there by surface flows contemporary to the conduit activity. Note the "bleeding" of lava from within the sheets of the primary roof and of the secondary sheets. Note also the reddening of the upper layers by invading air into the hot stack of lava sheets.

at this station. Above are much thicker pāhoehoe sheets, each with a ropy surface. These must have been added secondarily on top of the primary roof as surface flows, with the youngest one on top. At stations 54, 59 and 60 these sheets have even generated small conduits, exposed in the ceiling by breakdown. Thus the roof became several meters thick. At the entrance it is about 6 m thick. At station 51 (where the roof is punctured by breakdown and the ceiling is composed of ash) the entire pāhoehoe roof is about 5 m thick (see cross section in Figure 3). Consequently the roof was thick enough to allow considerable upward enlargement of the main passage by breakdown in the observed range of passage heights.

The third evidence for the importance of enlargement of the cave upward is the observation that the pāhoehoe sheets that were added to the primary roof are in fact contemporaneous with the activity of the flow. This evidence comes from the observation that these sheets all still were extruding residual melt that oozed out of the contacts between the sheets or from beginning contraction cracks forming various patches of black glazing (Fig. 11) ending in stalactites or creating small driplet spires on the ledges of walls (Fig. 12). Also the walls, from which the blocks of the collapsed pāhoehoe sheets derived, appear to be smoothed over by heat. They did not acquire a black glazing but they certainly must have been quite hot when collapsing.

Fig. 11. View of the side wall of Whitneys Cave with lava oozing out of cracks.

Fig. 12. Lava stalagmite made of lava that dripped from ceiling. Note that the site where it grew is on glazing that showed the lava level during the activity of the cave. Thus the lava was still hot even after the main activity ceased.

Conclusions

These observations together show that the cave must have experienced a considerable upward (and sideward) enlargement by breakdown of blocks from both the primary roof (which was removed entirely in many places) and from the secondary overburden of thick surface pāhoehoe sheets that were derived from the same flow event. These secondary sheets are quite thick and have generated blocks weighing tons (as seen by the blocks now littering the floor in many parts of the cave).

However, this conclusion leads to yet another question, and that is how the big breakdown blocks were removed through the comparatively small "valves" without clogging the conduit. This leads to the much-debated possibility of remelting. It costs a large amount of energy to melt basaltic rocks once crystallized. In the case of Whitneys Cave however, evidence shows that the roof (both the inflation-generated primary roof and the secondary cover of surface pāhoehoe sheets) was still hot and that the blocks generated from it did not need to be heated from ambient surface temperature but could still have had temperatures of above 800°C, thus saving a considerable amount of energy in the remelting process. It is interesting that the removal of the blocks must have been quite efficient, since only a few lava balls (coated fragments of breakdown like the block that looks like a dolphin) have been noticed throughout the cave.

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