Stephan Kempe, Ingo Bauer, and Horst-Volker Henschel - Pa'auhau Civil Defense Cave on Mauna Kea, Hawai'i - A lava tube modified by water erosion. *Journal of Cave and Karst Studies, v. 65*, n. 1, p. 76-85.

PA‘AUHAU CIVIL DEFENSE CAVE ON MAUNA KEA, HAWAII A LAVA TUBE MODIFIED BY WATER EROSION

STEPHAN KEMPE, INGO BAUER, AND HORST-VOLKER HENSCHEL
Institute for Applied Geosciences, University of Technology Darmstadt, Schnittspahnstr. 9, D-64287 Darmstadt, Germany; kempe@geo.tu-darmstadt.de

In 2000 and 2001, 2 large (1000 m long) cave systems were surveyed on the eastern, heavily eroded flank of Mauna Kea: The Pa‘auhau Civil Defense Cave and the Kuka‘iau Cave. Both caves occur in the Hamakua Volcanics, 200-250 to 65-70 ka old. They are the first substantial caves documented for lavas of this volcano and the first caves on the island of Hawaii showing extensive morphological signs of water erosion.

All observations lead to the conclusion that the Kuka‘iau Cave is erosional in origin (Kempe & Werner 2003). These observations include: missing lava tube features, a graded hydraulic profile, a base layer along which the major section of the cave seems to have developed, and allophane and halloysite that sealed the primary porosity causing a locally perched water table.

In contrast to this feature, the Pa‘auhau Civil Defense Cave originated as a lava tube. This is attested to by the presence of the typical morphologic elements of a lava tube, such as secondary ceilings, linings, base sheets, lava stalactites, and lava falls. Nevertheless, the cave was heavily modified by a stream that entered upslope and traversed much, but not all, of the cave. It left waterfall walls, large plunge pools, stream potholes, scallops, flutes, gravel, rounded blocks, and mud.

The finding of water-erosional caves in the lavas of Hawaii offers a new view on deep-seated water courses in volcanic edifices.

On Hawaii, hundreds of small and large lava tubes have been explored in the past 20 years, largely by members of the Hawaii Speleological Survey and the Hawaiian NSS Grotto. These tube systems are on the volcanoes of Kilauea, Mauna Loa, and Hualalai. Mauna Kea, however, remained somewhat of a blank spot speleologically. Old reports of caves being intercepted by water wells have not been sufficiently documented so far. Halliday (2000a, b) reported some small natural caves on Mauna Kea. Along the old Mamalahoa Highway west of Honoka‘a, along the road to Waipio Valley and near the power station at Honoka‘a there are a few artificial, cave-like excavations, where road building material such as cinders and aa were mined.

Hawaiian hydrology ranges from extremely humid to extremely dry on a single island. On the windward side of the Big Island, Mauna Kea's NE flank receives up to 2.3 m of rain per annum (1961-1990 average annual precipitation data, U.S. National Oceanic and Atmospheric Administration). This led, in spite of the highly porous nature of volcanic rocks, to the formation of perennial and occasional streams, which in turn have significantly dissected the eastern flank of Mauna Kea. The flank's morphology is characterized by several deep gulches and countless V-shaped gullies and stream ways that funnel the water straight to the ocean without forming large tributary river systems.

The last eruption on Mauna Kea occurred at the summit under the ice of the Last Glacial. The upper slopes of the volcano are composed of volcanics of the Laupahoehoe Series, <60 ka old, while the older Hamakua Series is exposed in the gulches of the Hamakua Coast (Wolfe *et al*. 1997). It is dated to between 200-250 to 65-70 ka BP and consists mostly of alkalic and transitional basalts. In the upper part of the volcano, glacial deposits are found as well. Any tubes on the lower flanks, therefore, predate the Last Glacial and formed at least several 10s of 1000s of years ago. Thus, they could have been invaded and plugged by younger lava, been filled by ash, or collapsed under the weight of overlying strata. Because of this anticipation, no systematic search has been made for caves on Mauna Kea as yet.

W.R. Halliday gained knowledge of the locally known Pa‘auhau Civil Defense Cave, and in 1998 a team of the Hawaii Speleological Survey visited it, exploring it to a mauka[1] end. The cave, as the name states, had been on the list of civil defense shelters during the cold war, and it was also visited extensively by ancient Hawaiians. They left stone piles, smaller and larger cairns, small platforms, upright stones, stone rings, and bits of charcoal from their torches. In 2001, Pa‘auhau Civil Defense Cave was fully explored and surveyed by a (Kempe *et al*. 2001).

In 2000, 2 more caves were found: ThisCave and ThatCave, also in the Hamakua Series. They were explored and surveyed by teams led by S. Kempe and M.S. Werner. In addition, geologic investigations were carried out in ThatCave by S. Kempe and I. Bauer in March 2001. In June 2002 the

[1] *mauka* = Hawaiian for “upslope”

sump between the caves was explored and both caves, now called Kuka'iau Cave, were connected. Kuka'iau Cave proved to be entirely of erosional origin, a novelty for lava caves (Kempe & Werner 2003). The story of the discovery of these caves and initial reports are given in Werner *et al*. (2000, 2003); Kempe (2000), and Kempe *et al*. (2001).

GENERAL LAVA TUBE MORPHOLOGY OF PA'AUHAU CIVIL DEFENSE CAVE

The map of Pa'auhau Civil Defense Cave shows a branched pattern (Figs. 1, 2). Total passage length is 1000.5 m (988 m horizontal). The ratio between the main passage length to those of the side passages is 1.37. Total vertical extent is 48.9 m, and the slope along the main survey line is 4.87° (5.56° if calculated for the distance as-the-crow-flies). The detailed statistics of Pa'auhau Civil Defense Cave are given in Table 1.

The present entrance, situated at the makai[2] end of the cave, looks out into a modern canyon (Kahawaili'ili'i Gulch). In the gulch wall, left of the entrance, a small cut-around opens up leading back into the cave a few meters. Its opening is perched near the ceiling a ~2 m above the floor, thus illustrating where the lava sheet had initially formed conduits and how much the lava had cut down during its active flow period. The main passage is ~2 m high and 2-3 m wide near the entrance (Fig. 3) and gradually widens mauka. It then trends south for 348 m. There, mauka of Station 40 (abbreviated St. in the following), the cave branches: To the east, tributary passages join (Sidepasssage, Collector-Alpine Streamway, Sandpassage-Unhawaiian Crawls) and to the west a distributary passage (Mudcrawl) leads off. The main passage rises farther until it ends 580 m mauka and 49 m above the entrance. Interestingly, this passage ends at an apparently solid wall. A small hole that blows air, however, suggests further passage mauka. Possibly the main passage is genetically only a side passage that was blocked by lava intruding it from the main lava feeder beyond.

The main proof that this passage was not the main lava feeder is given by the situation above Plunge Pool 4: The floor of Sidepassage is lower than that of Stone Ring Hall in the main passage (compare Fig. 4). Apparently lava from Sidepassage back-flooded mauka into Stone Ring Hall, suggesting that actually Sidepassage is the primary and last active lava feeder. The mauka end of Sidepassage is collapsed, but it may have connected into Alpine Streamway (see dashed connection on Fig. 1). The mauka end of Alpine Streamway is blocked by breakdown composed of large blocks. Roots are visible, and kukui nut shells gnawed open by rats are abundant, suggesting that we are viewing the inner side of a collapse along the northern Kahawaili'ili'i gulch wall. Therefore, the main lava feeder cannot be explored any farther mauka. In June 2002, we searched the gully hoping to locate both the mauka exit of the cave and the main lava feeder. We found a place blocked by rounded boulders ~5 m above the stream bed that could be the blocked exit of the cave. We also found, on the opposite wall, a ~30 m long small lava tube running mauka at the level of the cave. It could represent another tributary branch of the cave. We did not find, however, the main feeder. This is not surprising, considering the collapsed nature of the gully walls.

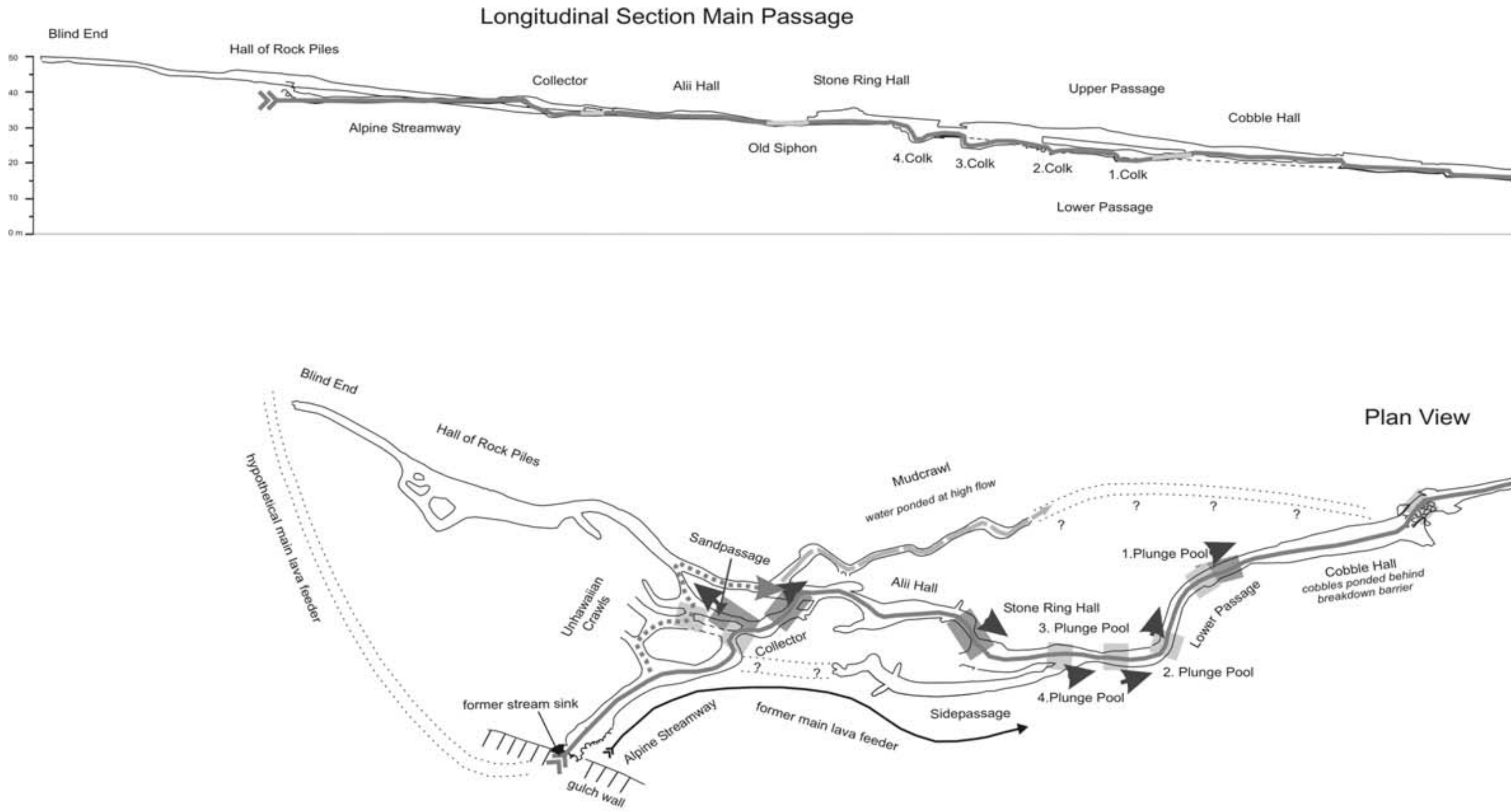
All-in-all the general pattern of the cave displays typical lava tube characteristics (recently summarized in Kempe 2002). This conclusion is also corroborated by the medium- to small-scale tube morphology. Most importantly, we find 2 sections of secondary ceilings. The first one occurs just mauka of the entrance and is 16.6 m long. The second starts above St. 26 and extends mauka for 49 m. There follows a section where the secondary ceiling collapsed, but its remains can be seen high up on the walls as ledges. Actually these ledges connect into the back-flooded lava sheets of Stone Ring Hall, illustrating that the lava of the secondary ceiling must have come from a surge of lava out of Sidepassage as explained above. Secondary ceilings form whenever the lava has cut down so much that an airspace develops above the flowing lava. If enough airflow can be established, then the lava can solidify in the cave, forming a secondary ceiling (Kempe 1997). Secondary ceilings are therefore very good indicators that a lava cave is, in fact, a lava tube created by flowing lava.

A score of other features typical of lava tubes occurs as well: Linings with vertical lamination along the wall, ledges of former lava stands along the sides of the passage, small lava

Table 1: Statistics of the survey of Pa'auhau Civil Defense Cave, March 2001.

	Stations	Real (m)	horizontal (m)
Main survey line	1 to 74	579.62	573.37
Cut-around at entrance	3 to 5	5.33	5.33
1. secondary ceiling	3 to 8	16.62	16.56
Recess at Cobble Hall	23 to 24	5.94	5.94
2. secondary ceiling	26 to 36	45.25	44.39
Minus parts of St. 26 to 27		-7.50	-7.00
Sidepassage	44 to 55	57.69	56.90
Branch	59 to 99a	8.55	8.50
Alpine Streamway	75 to 93a	88.24	85.08
Treemold	76 to 78	3.00	3.00
Squeeze	79 to main passage	4.00	4.00
Sandpassage	80 to 65	26.70	26.29
Branch	83 to 85	6.84	6.83
Unhawaiian Crawls	82 to 90	37.78	37.68
Mudcrawl	63 to 110	77.28	77.07
Branch	67 to 111a	10.70	10.66
Cut-around at end	116 to 113	27.45	27.30
Cut-around at St. 71	Estimated	4.00	4.00
Connection	112 to 70	3.00	3.00
sum:		1000.49	988.90
Side passages sum:		420.87	415.53
As-the-crow-flies (horizontal)			502.62
Sinuosity main passage			1.14
Vertical	1 to 74	48.93	
Slope ($\tan^{-1}$ 48.93/573.3)			4.87°
Slope ($\tan^{-1}$ 58.93/502.62)			5.56°
Main passage/side passage ratio			1.37
Secondary ceiling ratio			0.11
Coordinates of begin of path to entrance			020°05.153'N 155°26.275'W

[2] *makai* = Hawaiian for "downslope"



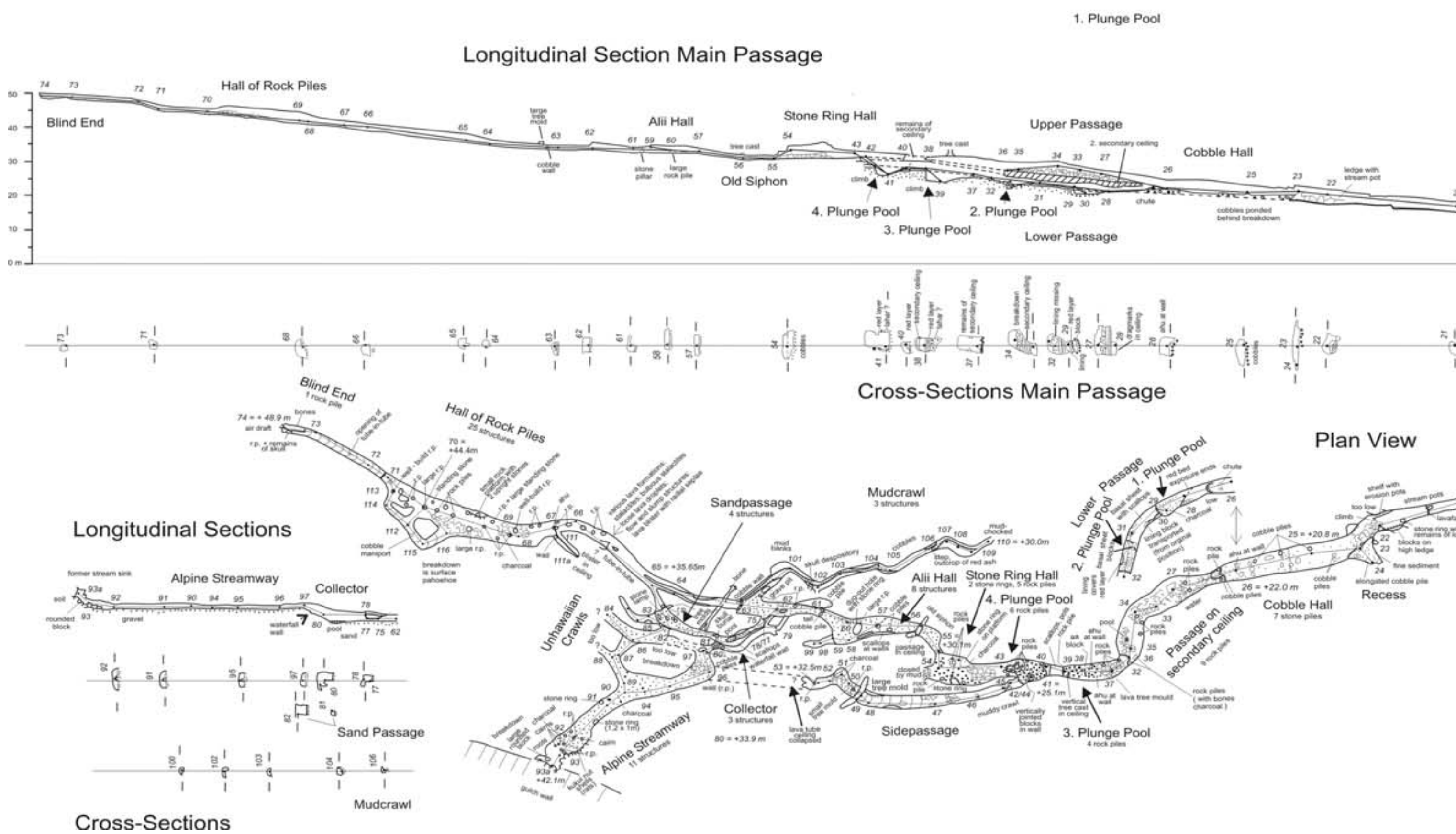


Figure 1 (bottom). Map and sections of Pa'auhau Civil Defense Cave, Hawaii.

Figure 2 (top). Paleohydrologic Map of Pa'auha

Fig. 2: Reconstruction of Paleohydrography

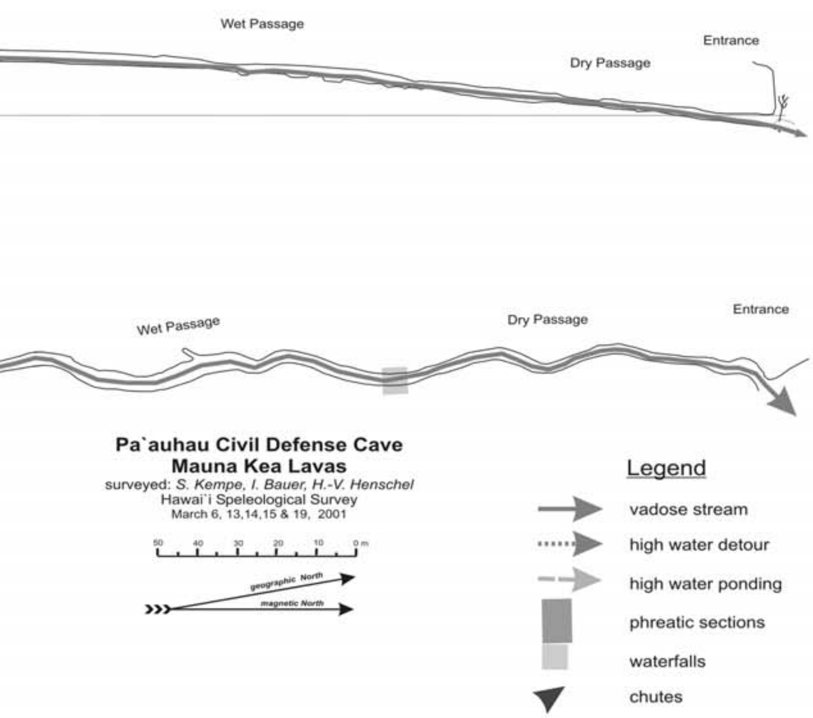
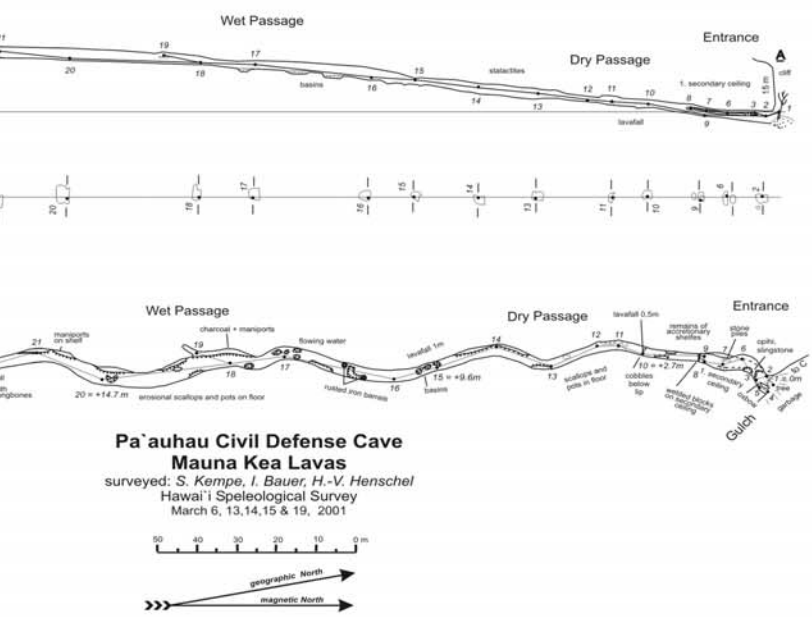


Fig. 1: Detailed Map and Sections



u Civil Defense Cave.

falls (in the entrance series), tube-in-tube features on the floor (at the upper end), pahoehoe flow lobes on the floor (also at the upper end), abundant lava stalactites, and loose lava droplets in places (near St. 95). All these features together establish beyond doubt that the cave is a lava tube by origin.

EROSIONAL MORPHOLOGY OF PA'AUHAU CIVIL DEFENSE CAVE

A second set of features, however, is observed in the cave, indicating that it was secondarily sculptured by flowing water (Fig. 2). These features are noticed on the floor of the cave beginning just beyond the entrance. Scallops and stream potholes, partly filled with rounded stones, are the most obvious of these features. Closer inspection shows that the entire surface of the bottom sheet of the lava tube is smoothed and that it has lost its original pahoehoe morphology. Also, the lower stretches of walls are smoothed. These signs of erosion become more prominent as one proceeds into the cave. At several places, for example at the small lava fall at St. 10, erosion has cut through the bottom lava sheet exposing underlying sediment (Fig. 5). Shortly, the erosion potholes become larger, forming elongated stream potholes (Fig. 6) and 1-2 m long basins, often up to 1-m deep (Fig. 7). Initially the passage is dry, but beyond St. 16 water stands in the potholes and a little water even runs along the floor, spilling from pothole to pothole. None of this water ever makes it to the entrance, apparently because this flow seeps down and out of the cave via floor cracks. These basins, partly filled with water, apparently gave rise to the idea to use the cave as a civil defense shelter. At least 2 large iron barrels were brought into the cave in the 1950s to serve as emergency water containers; some boards and supplies in tin cans were placed in this part of the cave. Everything is now so rusted and decayed that only mulch and rust remains.

At St. 22, we encounter an old (i.e., predating the water-worn morphology) barrier caused by breakdown blocks. The water had to flow along the western wall and cascaded down the blocks and along a ledge, ~80 cm above the floor. On this ledge several potholes occur, one of them passes clear through the ledge (Fig. 8). Beyond the breakdown blocks, the floor of the cave is much higher and is composed of rounded blocks, gravel, sand, and mud (Cobble Hall). Apparently, the gravel transported along the cave was caught behind the breakdown blocks, forming a natural dam. This explains the lack of substantial gravel beds in the lower section of the cave. From St. 23 onward, gravel, sand, mud, and rounded blocks are common in the cave.

With the beginning of the second secondary ceiling, the picture of the cave floor changes once more: Up to the first branch of the cave at St. 40, we encounter 4 large

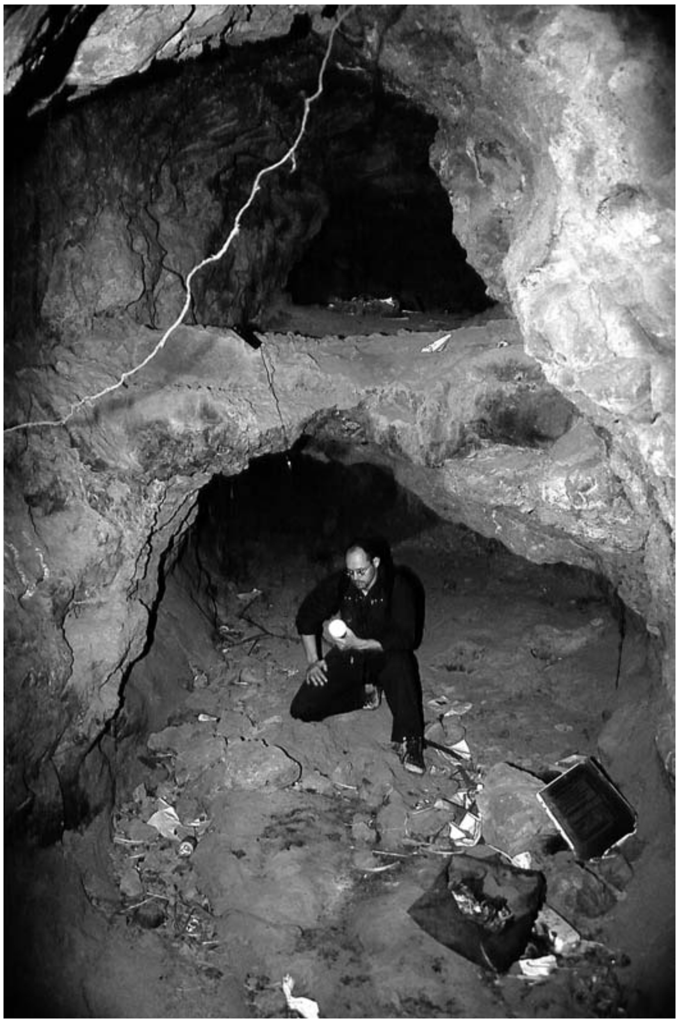


Figure 3. Entrance of Pa‘auhau Civil Defense Cave; note the beginning of the first secondary ceiling above the head of Bauer.

plunge pools. In each of them, the bottom sheet of the cave, 20-40 cm thick, has been removed completely, and the water has excavated up to 3 m into the underlying sediment best described as a diamict (Figs. 4 & 9): It contains disintegrated aa blocks imbedded in fine-grained, non-consolidated material. Its origin remains unclear, it could be a mudflow, a lahar, the blocky layer of an aa flow filled with ash, or a tuff.

The mauka end of each pond is a steep wall, exposing the diamict nicely. It is reddish down to a depth of ~20 cm, whereas below the diamict is brown. This reddening may have been caused either by weathering and soil formation on the surface of the diamict or may signify oxidation caused by the overriding hot lava. The makai end of the plunge pools is formed as a chute along which the water dragged gravel and boulders. Any gravel originating upstream must have passed these plunge pools. Possibly the material excavated in the plunge pools alone provided enough material to account for the gravel pond behind the breakdown barrier and not much gravel needed to be imported from farther upstream.

Figure 4. View mauka into the Dry Passage: Station 10 is on the left side of the small lava fall in the foreground. Water erosion has cut a pothole into the lavafall and tugged stream-worn pebbles into the pocket below the lip (note Bauer for scale).

The wall of Plunge Pool 4 leads, on the eastern side, up into Sidepassage, which does not show any sign of erosion by flowing water. It also opens up into the Hall of Stone Rings on the western side, from where the water cascaded down 4 m into the plunge pool (Fig. 4). The floor of the Hall of Stone Rings is much thicker (4 lava sheets) due to the back-flooding of lava as explained above; therefore, the floor dips down at the mauka end of the hall where the intruded lava laminae apparently end. This caused an upward flow of the water, flooding the passage beyond up to the ceiling, creating a sump (Old Siphon). A similar sump, with signs of erosion on the ceiling, occurred also at the makai end of the second secondary ceiling (St. 26-28).

In the main passage, beyond Old Siphon, we enter Ali‘i Hall, a clean-washed section of the cave covered by fine-grained sediment. After another constriction, a round tube, ~1 m in diameter, branches to the east at floor level (Fig. 10). All sides of the tube are polished, showing that it is a former sump as well. Sediment was transported upward on a chute in front of it. Beyond the tube, one can stand up again and enter a canyon-like room, the Collector (Fig. 11). Its walls show large scallops, and the floor is covered with coarse sediment. At this passage's end, again a former sump, a low crawl leads upward into Sandpassage. On the eastern side, one can climb up a former waterfall headwall, nicely scalloped and dotted with stream potholes. From there, one enters the Alpine Streamway. The Alpine Streamway's floor is blanketed with coarse-grained sediment and cobbles, some of them up to 50 cm in diameter. The sediment floor is nearly horizontal; possibly the sediment is impounded in a once deeper passage connecting into the collapsed Sidepassage. The present connection into the Collector follows an upper level of the lava tube, a level that is also seen at the makai end of the Collector, where 2 tubes led flood water into Ali‘i Hall. The mauka end of the Alpine Streamway is now blocked by breakdown on top of the large

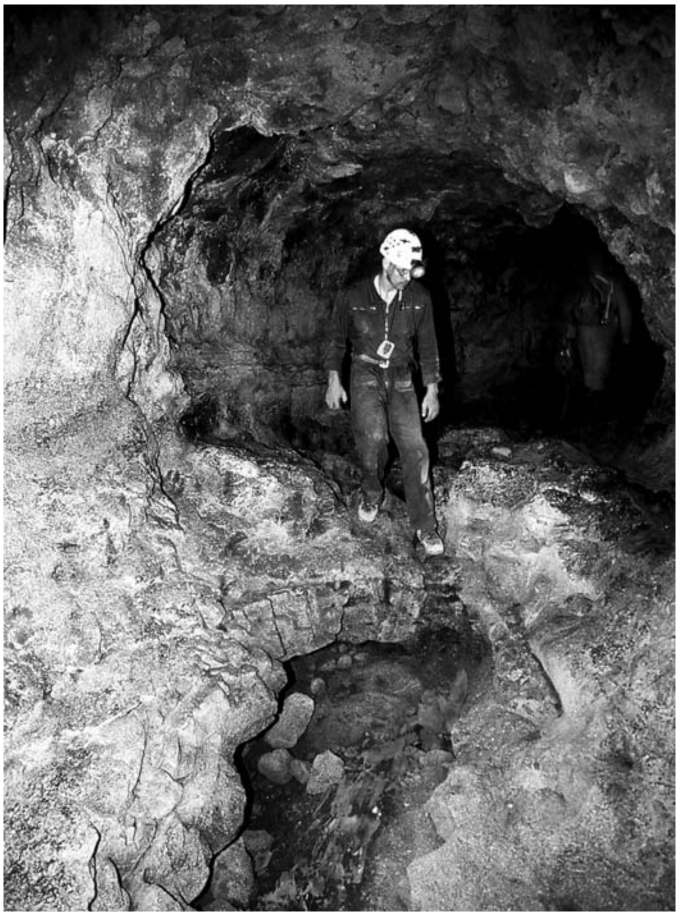


Figure 5. View mauka into the Wet Passage between St. 15 and 16. Large basin cut into the bottom sheet of the lava tube by water (Bauer for scale).

Figure 6. Potholes with cobbles in the Wet Passage (note hand for scale).

stream worn boulders. This area was a former sink along the Kahawaili‘ili‘i Gulch stream, feeding all or part of its waters into the lava tube.

Mauka of Alpine Streamway and Collector, we find the Unhawaiian Crawls (named because these are the only sections of the cave showing no evidence of Hawaiian visitation) and the Sandpassage. The Unhawaiian Crawls are very low, and to survey them we had to shift cobbles out of the way before squirming through. The Unhawaiian Crawls lead to another waterfall wall entering the Sandpassage. Both Unhawaiian Crawls and Sandpassage contain pebbles and cobbles, unlike the Collector. Apparently these passages were high water detours, moving water uphill when the collector and its drains could not transport all of the inflowing water. From the mauka end of the Sandpassage, water overflowed back into the main passage (Fig. 2).

During such flooding events, water also entered the Mudcrawl, where it partially ponded. Mudcrawl was a distributary lava tube that possibly connected further makai into Cobble Hall. If so, this passage’s lower end is masked by ponded gravel and fine-grained sediment fill in the lower reaches of Cobble Hall. Therefore, the water could not be discharged quickly once the Mudcrawl filled during flooding, and the suspended sediment settled, making Mudcrawl particularly muddy. In recent times, a seepage-water-fed small stream has removed some of the mud, so that the former rock floor is visible. At one place, even the bottom lava sheet has been eroded through, and the underlying red diamict is visible. The Mudcrawl ends in an impenetrable, muddy choke with no air draft present.

There is no evidence of extensive water flow in the area above the junction of Sandpassage with the main passage (i.e., mauka of St. 65). At the blind mauka end, a pit is encountered that contains some sediment, partly dug up by Hawaiians. It may have been washed in through a small hole with a strong air draft at the upper end of the pit.

ADDITIONAL GEOLOGIC OBSERVATIONS

Rock and sediment samples were taken in order to characterize the geology of the cave. Grain size analysis was conducted on 5 samples. Figure 13 shows 2 samples from the diamict profile of Plunge Pool 4 (compare Fig. 4) plus 3 samples from fluvial sediment.

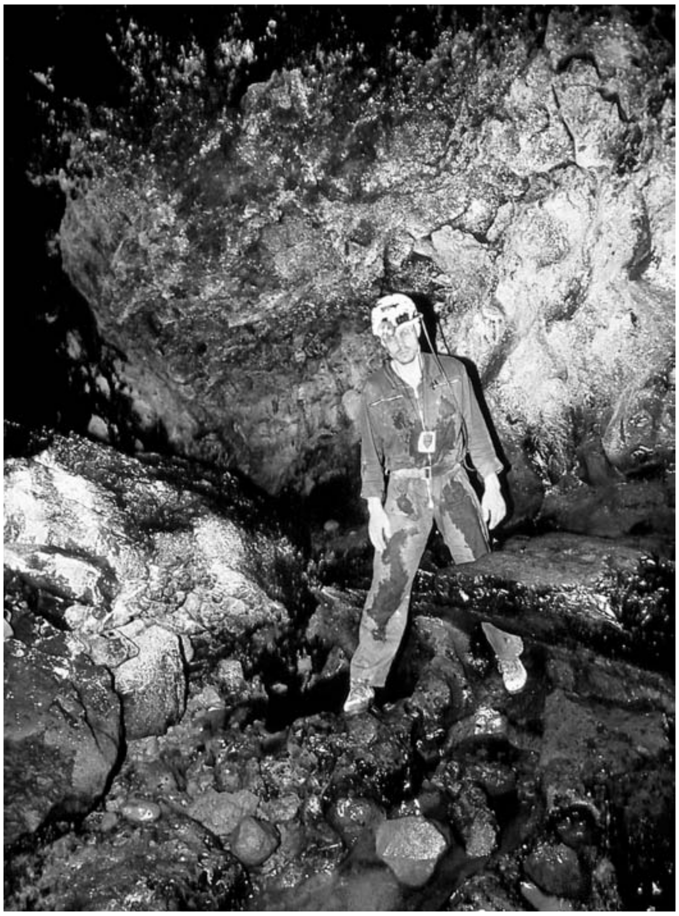


Figure 7. Ledge at St. 22 through which a stream pothole has drilled (Bauer standing with one leg in it).

Figure 8. View mauka out of Plunge Pool 1 onto the face of a former waterfall. Kempe sits on the eroded bottom sheet of the lava tube. The plunge pool eroded into reddish sediment below the lava flow, forming a circular outcrop from the left to the right side of the pool. Note the low ceiling; this is because Plunge Pool 1 is below the second secondary ceiling. Water flow has eroded a semicircular ceiling as in a phreatic tunnel.

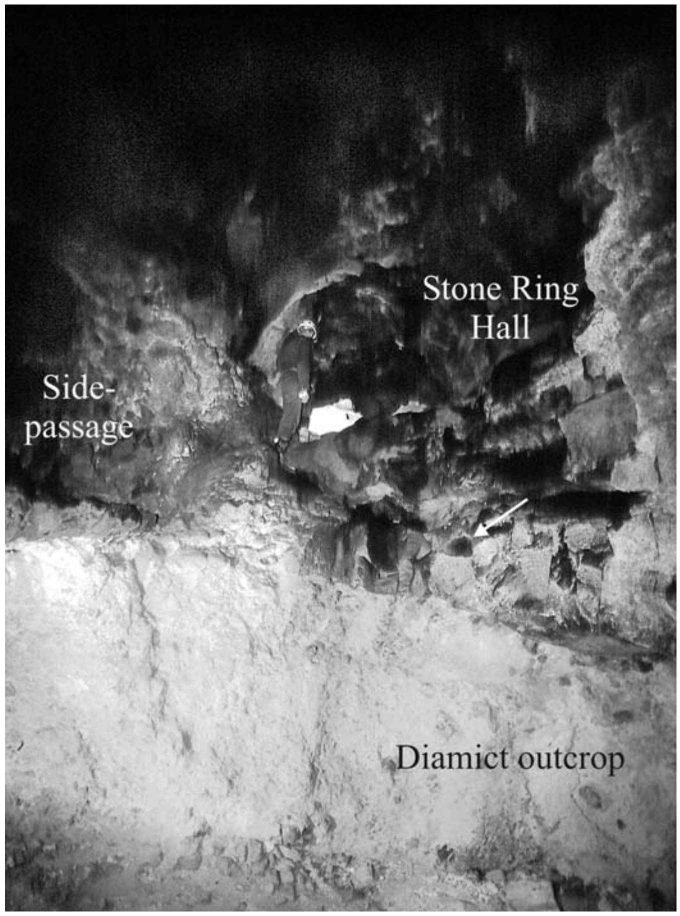


Figure 9. View mauka out of Plunge Pool 4 onto the 4 m high wall of a former waterfall. To the left, Sidepassage branches off; to the right, the Stone Ring Hall is entered. Bauer stands on several lava sheets (arrow) that have back-flooded the floor of the Stone Ring Hall, illustrating that Sidepassage was the main terminal lava feeder. The exposed, reddish diamict below the bottom sheet of the lava tube grades into brownish colors below. The sediment is composed of large blocks and fine weathered ash.

The two samples from Plunge Pool 4 are quite different; P1 (sample size 170 g) represents the red-brown matrix from the surface of the profile, while P2 (175 g) was recovered from the brown matrix at a depth of 2 m. The larger components (>1cm) enclosed in the matrix were not incorporated in the analysis. These components are rather weathered but they appear to be angular to sub-angular pieces of lava, not rounded by water transport. The <1 cm fraction of sample P1 is very fine-grained, and almost 75% of its mass is silt- or clay-sized. The <1 cm fraction of sample P2 is much more coarse-grained and shows a more linear appearance on the grain size plot. This difference within the same diamict could have come from sustained weathering in the top layer with enrichment of the paleosoil in fine-grained iron oxides and clay minerals through the disintegration of coarse-grained feldspar and augite. This would indicate that the diamict was an open system for a long

Figure 10. View from Station 62 into the phreatic outlet of the Collector (Kempe inside of Collector for scale). Note the smooth floor covered with water deposited sandy sediment.

Figure 11. View mauka into the Collector. Person stands on the waterfall wall from where the water plunged out of the Alpine Streamway into the Collector. Note pool at floor and stream worn wall with large scallops on left hand wall (Kempe at far end of Collector for scale).

Figure 12. View into the eastern end of the cast of a large tree (most probably a Koa tree) mauka of St. 63. Kempe crouches inside the rootstock, which branches into three principal roots. Note the casts of the bark on the right hand side. The tree was uprooted by the lava flow and came to rest across the flow path of the lava. The primary tube established itself just under the tree trunk.

time (i.e., it is a true paleosoil). From the many tree casts in the lava above the diamict (i.e., in the lava that formed the tube), we know that the diamict carried a fully grown forest (see large tree mold, Fig. 12), indicative of a longer time gap between the deposition of the diamict and the emplacement of the tube-bearing lava on top of it.

Three samples (P3, P4, P5; 742 143, 34.4 g, respectively) from the fluvial floor sediment of the cave were also analyzed for their grain-size distribution (Fig. 13). P3 from the Collector and P4 from the main passages near the entrance to Mudcrawl show high percentages of coarse material (more than 95 and 85% is sand and gravel, respectively), while the sample (P5) from the Mudcrawl has only 70% in the coarser fraction, mostly sand, hardly any gravel, illustrating that the water ponded in the Mudcrawl. On some of the sediment and rock samples, x-ray diffraction analyses and C-N-S analyses were made (Table 2a, b).

Sample P6 is the only one representing the lava that formed the cave. It was taken from the bottom sheet (makai of Plunge Pool 4), the layer of lava that solidified on the sediment. It is a rather hard, dark gray, fine-grained, and not very porous lava. The olivine does not form conspicuous phenocrysts, but feldspars are macroscopically visible. All other samples are devoid of olivine and have higher plagioclase and augite concentrations and contain appreciable amounts of hematite. The increased plagioclase content probably is caused by differential weathering with olivine being lost first, then augite, and then feldspar. This is nicely shown in sample P1, representing the former paleosoil, where both olivine and augite have disappeared. The increased hematite content has 2 causes. In samples P8 and P9, it is primary hematite, precipitating last on the surface of the solidifying lava, giving it its bluish hue, while in the other samples hematite is a

Table 2: A) Results of x-ray-diffraction analyses of rock samples from Pa‘auhau Civil Defense Cave. Results are estimated weight percents.

Sample March 2001	Color of ground sample	Plagioclase	Augite	Olivine	Hematite	Clay	Residue
P1, red-brown sediment, Plunge Pool 4, surface	Red-brown	29%	-	-	59%	12% Halloysite	High x-ray amorphous component
P2, gray-brown sediment Plunge Pool 4.2 m depth	Light gray, brownish	41%	13%	-	31%	10% Halloysite	5% undeter.
P3, fluvial sediment floor of Collector	Light brown	32%	31%	-	14%	9% Halloysite 8% Donathite*	6% undeter. Large x-ray amorphous component
P4, Fluvial floor sediment, main passage between St. 62 and 75	Light brown	46%	26%	-	15%	8% Halloysite	5% undeter. Large x-ray-amorphous component
P5, Fluvial floor sediment, Mudcrawl, St. 100	Light brown	32%	42%	-	19%		7% undeter. Large x-ray amorphous component
P6, Basal sheet of cave, St. 41, Plunge Pool 4, dark gray, low porosity, no larger phenocrysts	Gray-greenish	50%	11%	22%	5%	8% Halloysite	4% undeter. Very large x-ray amorphous component
P8 Wall of cave at St. 42, irregular lava, low porosity, light gray, rather weathered and soft	Light gray	27%	25%	-	24%	-	24% undeter. Large x-ray amorphous component
P 9 Stalactite and glazing, fragile, weathered, from inside of tree mold mauka St. 63.	Gray brownish	32%	29%	-	22%	-	7% undeter. Large x-ray amorphous component

* Donathite ((Fe,Mg)(Cr,Fe)$2O_4$)

Table 2: B) Results of carbon, nitrogen, sulfur elemental analyses of sediment samples from Pa‘auhau Civil Defense Cave (weight percent).

Sample	C	N	S	C/N
P1	0.031	0.052	0.38	0.60
P2	0.035	0.057	0.55	0.61
P3	0.15	0.072	0.11	2.05
P4	0.25	0.062	0.84	4.08
P5	0.40	0.11	0.009	3.64

weathering product causing a brownish or red-brown coloration.

Halloysite (a clay mineral) is present in appreciable quantities. Together with hematite, it is among the products of silicate mineral weathering and common in weathered basalt of Hawaii and elsewhere (e.g., Patterson 1971). In the sediment underlying the cave, it is highest in concentration, but it also occurs in the fluvial sediment that is composed of material washed into the cave from weathered rocks higher on the mountain. In addition, there is a large x-ray amorphous fraction, most probably allophane, as described in the paper by Kempe and Werner (2003).

The high halloysite content in the sediment exposed in the plunge pools is important for the speleogenesis of the cave. It could have closed the pore space of the sediment, therefore enabling the stream to flow in the cave without sinking.

Overall, the samples contain only very low concentrations of C, N, and S (Table 2B). The lowest C concentrations of 0.03% were found in the underlying diamict in the profile of Plunge Pool 4 (P1 & P2), illustrating that the diamict is not a cumulative body of fluvial sediments. Possibly it is sort of lahar, or mudflow originally incorporating unweathered ashes and lava blocks. Compared to these samples, the fluvial sediment (P3-P5) has a higher, but still very low C concentration. The highest C content was found in the sample from the Mudcrawl (P5), which has the finest sediment. The same distribution, but with a lower spread in values, is found for the total nitrogen content. The sulfur values vary greatly and are difficult to interpret. The C/N ratio is <1 for P1 and P2, indicative of inorganic nitrogen (nitrate). Even in the fluvial sediment, the ratio is rather low but more toward the composition found in soils (C/N ~6).

The composition of the diamict exposed in the plunge pool walls does not differ much from that of the solid rock; it, therefore, is most likely volcanic ash. Due to the presence of large, irregular lava pieces in the ash, it most probably did, however, not originated as an ash fall. Either the larger fractions represent aa rubble into which later ash was washed in, or the entire layer is a sort of lahar or mud flow of mixed coarse components and fine-grained material.

AGE OF THE SYSTEM

So far we can only be sure that the Pa‘auhau Civil Defense Cave is older than 60 ka, because its lava layer is a member of the Hamakua Volcanic Series (Wolfe *et al*. 1997). Eventually,

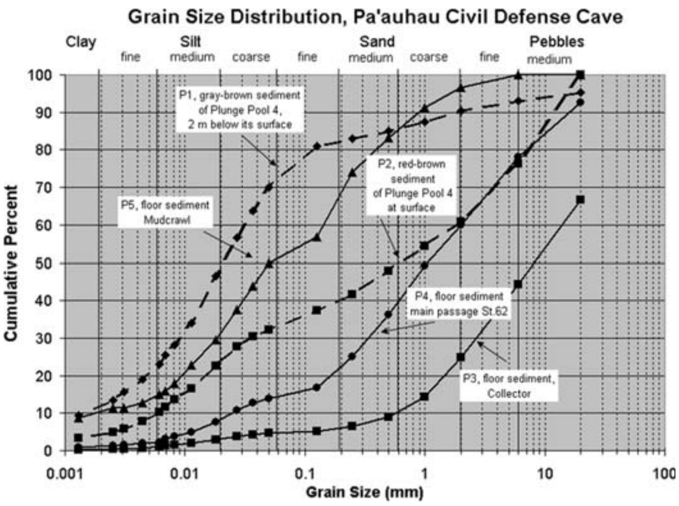


Figure 13. Plot of grain-size analyses for 5 samples from Pa'auhua Civil Defense Cave. Broken lines indicate sediment underlying and predating the cave, solid lines denote fluvial sediment from within the cave.

better dates both for the formation of the lava conduit and of the erosional event may be obtained. This can be done by applying optically stimulated luminescence analysis to both the sediment underlying the lava tube (accessible in the plunge pools) and the fluvial sediment in the cave. We already have taken 4 samples in the dark, which can be used toward this purpose if dating can be funded.

As yet, one can only say that the erosional phase must be quite old, in spite of the fact that the erosional morphology looks very fresh, specifically in the inner part of the cave. Three clues suggest the antiquity of this erosion event: (i) the gulch is now about 20 m deeper (at the cave entrance) than at the time of the hydrologic activity in the cave; (ii) the erosion is older than the Hawaiian usage of the cave because none of their stone piles, even where placed in the middle of the vadose stream course, are disturbed; and (iii) there is a pile of soil in front of the entrance that was washed down from the plateau above. Apparently no significant amount of water has issued from the cave for some time because this pile of soil debris would have been washed away. Possibly the erosional phase dates as far back as the Last Glacial (i.e., to the time when the gulch had a higher downcutting rate than today due to snowmelt events or due to a much less extensive vegetation cover). At any rate, the Pa'auhau Civil Defense Cave is certainly the oldest substantial lava conduit cave yet discovered on the island of Hawaii.

ACKNOWLEDGMENTS

We thank M.S. Werner, W.R. Halliday, and O. Fulks for continuous and profound help in the field, R. Apfelbach, for XRD analyses, G. Schubert for grain-size measurements, R. Brannolte for CNS analyses and E. Wettengl for help in drawing the maps, all in the Institute of Applied Geosciences, Darmstadt. We thank B. Rogers and G. Moore for their thorough reviews.

REFERENCES

Halliday, W.R., 2000a, Kalopa State Park stream conduit caves: Hawaii Speleological Survey Newsletter, v. 8, p. 4.

Halliday, W.R., 2000b, A lava tube stream conduit system on Mauna Kea Volcano, Hawaii: Hawaii Speleological Survey Newsletter, v. 8, p. 5.

Kempe, S., 1997, Lava falls: A major factor for the enlargement of lava tubes of the Ai-la'au shield phase, Kilauea, Hawaii: Proceedings 12. International Congress of Speleology 10.-17. Aug. 1997, La Chaux-de-Fonds, Switzerland, v. 1, p. 445-448.

Kempe, S., 2000, Expedition report, Hawaii March 2000: Hawaii Speleological Survey Newsletter, v. 7, p. 25-29.

Kempe, S., 2002, Lavaröhren (Pyroducts) auf Hawai'i und ihre Genese, in W. Rosendahl & A. Hoppe (eds.), Angewandte Geowissenschaften in Darmstadt: Schriftenreihe der deutschen Geologischen Gesellschaft, Heft 15, p. 109-127.

Kempe, S. and Werner, M.S., 2003, The Kuka'iau Cave, Mauna Kea, Hawaii, created by water erosion, a new Hawaiian cave type: Journal of Cave and Karst Studies, v. 53, n. 1, p. 53-67.

Kempe, S., Bauer, I., and Henschel, H.V., 2001, Expedition report, Hawaii, March 2001: Hawaii Speleological Survey Newsletter, v. 10, p. 3-10.

Patterson, S.H., 1971, Investigations of ferruginous bauxite and other mineral resources on Kauai and a reconnaissance of ferruginous bauxite deposits on Maui, Hawaii: U.S. Geological Survey Professional Paper 656, 74 p.

Werner, S., Kempe, S., Henschel, H.-V., Stankiewicz, P., Elhard, R., Strait, M., and Elhard, J. 2000, ThisCave and ThatCave: Hawaii Grotto News, v. 9, n. 2, p. 13-17.

Werner, S., Kempe, S., Henschel, H.V., and Elhard, R., 2003, Kuka'iau Cave (alias ThisCave and ThatCave): Exploration report of a lava cave eroded by water, a new type of Hawaiian cave: National Speleological Society News, in review.

Wolfe, E.W., Wise, W.S. and Dalrymple, G.B., 1997, The Geology and Petrology of Mauna Kea Volcano, Hawaii: A study of postshield volcanism: U.S. Geological Survey Professional Papers 1557, 129 p. + 4 pl.