

THE KUKA'IAU CAVE, MAUNA KEA, HAWAII, CREATED BY WATER EROSION, A NEW HAWAIIAN CAVE TYPE

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In 2000 and 2001, two large (each ca. 1000 m long) cave systems have been surveyed on the eastern, heavily eroded, flank of Mauna Kea: The Pa'auhau Civil Defense Cave and the Kuka'iau Cave (at first called ThatCave/ThisCave System). Both caves occur in the Hamakua Volcanics, 200-250 to 65-70 ka old. They are the first substantial caves documented for lavas of Mauna Kea and the first caves on Hawai'i showing extensive morphological signs of water erosion.

The Pa'auhau Civil Defense Cave is a lava tube, as attested by the presence of the typical morphological elements of lava tubes, including secondary ceilings, linings, base sheets, stalactites and lava falls. Subsequently, the cave was modified erosionally by a stream which entered upslope and traversed much, but not all, of the cave, leaving waterfalls, waterfall ponds, scallops, gravel, rounded blocks and mud (Kempe et al. 2003). In contrast the Kuka'iau Cave – a still active stream cave with a vadose and phreatic section - is essentially erosional in origin. This is concluded from the geology of the strata exposed in the cave and from its morphology: At the upper entrance the cave is situated in a thick series of aa and the lower section was created by removing aa and diamict layers, therefore excluding the possibility that the cave developed from a precursor lava tube. Also, in its phreatic section, the cave makes several right angle turns and moves upward through a series of pahoehoe sheets, unlike any lava tube. Furthermore, a base layer can be followed along which the major section of the upper cave has developed. Allophane and halloysite – minerals produced by weathering - helped in sealing the primary porosity of this base layer causing a locally perched water table. Water moving along this base layer on a steep hydraulic gradient through the interstices of aa and through small pahoehoe tubes exerted a high pressure on the porous diamict of the lower cave, causing its erosional removal. Our observations of water erosional caves in lavas of Hawaii offer a new perspective on deep-seated water courses in volcanic edifices.

On Hawaii, hundreds of small and large lava tubes have been explored in the last 20 years, largely by members of the Hawai'i Speleological Survey and the Hawaiian NSS Grotto. These tube systems are located on 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 documented sufficiently so far. Along the old Mamalahoa Highway and along the road to the Waipio Valley Outlook west of Honoka'a there are a few artificial caves, but they are former quarries where road building material such as cinders and aa was mined.

Hawaiian microclimates vary widely from extremely humid to extremely dry conditions on the same island. On the windward side of the Big Island of Hawai'i Mauna Kea's NE flank receives up to 90 inches of rain per annum (1961-1990 average annual precipitation Data, U.S. National Oceanic and Atmospheric Administration). This has led, despite the highly porous nature of volcanic rocks, to the formation of perennial and episodic streams, which in turn have significantly dissected the eastern flank of Mauna Kea. Its morphology is characterized by several deep gulches and countless V-shaped gullies and streamways, which 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, i.e., during the Last Glacial. Any lava tubes that have formed

on the lower flanks are therefore older and may have formed several tens of thousands of years ago. Thus, such tubes, if any, should be either invaded and plugged by younger lavas, filled by ashes, or should have collapsed under the weight of overlying strata. Therefore, no systematic search was made for caves on Mauna Kea. When the first caves on Mauna Kea came to the notice of the Hawaiian Speleological Survey in 1995, this came as quite a surprise. These were two caves in Honoka'a and the Civil Defense Cave at Pa'auhau. First rough maps were published by Werner, 1997. Further findings, three small caves in Kalopa State Park and a larger system in the Hamakua Forest Reserve were reported by Halliday (2000 a, b). Pa'auhau Civil Defense Cave was studied in detail in 2001 (Kempe et al. 2003) and turned out to be a lava tube heavily impacted by water erosion.

In March 2000 Robert van Ells told M.S. Werner about another cave on Mauna Kea (Werner et al., 2000; Kempe et al., 2001). He reported having entered through a pit and then having exited makai¹ from a resurgence by swimming through a small pond. We relocated these two entrances on March 15th 2002. The cave was initially called ThisCave because we suspected that the cave already had a local name. Because it serves as the source of a stream at flood, we concluded that

¹ makai = Polynesian for "towards the sea" i.e., downslope

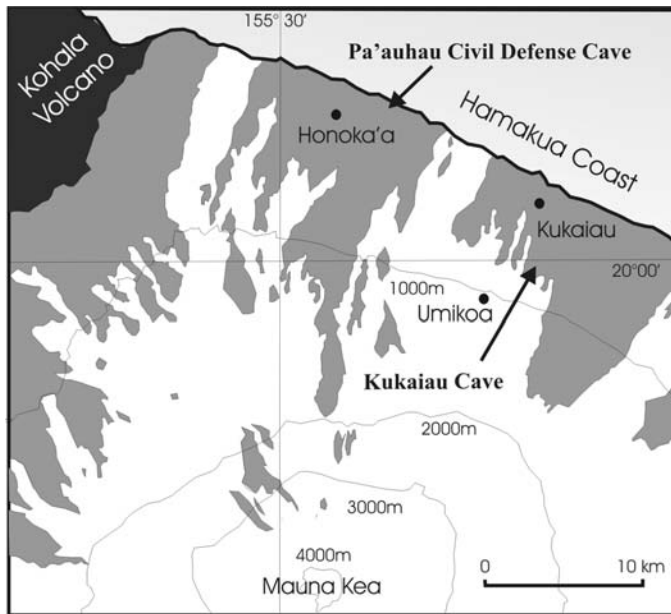


Fig. 1: Location of Kuka'iau Cave and Pa'auhau Civil Defense Cave and geological map of the Northern section of Mauna Kea. The dark gray area represents the outcrops of the Hamakua Volcanics and the white area represents the distribution of the overlying Laupahoehoe Volcanics (redrawn according to Wolfe *et al.* 1997).

there must be a stream sink mauka² as well. M.S. Werner then scouted the area and found the sink in a creek bed leading to a large vadose underground stream passage. It was provisionally called ThatCave. None of the ranchers interviewed knew about this entrance even though it is quite obvious and fences run nearby. In 2000 ThisCave and ThatCave were explored and surveyed by teams led by S. Kempe and M.S. Werner. In addition geological investigations were carried out in ThatCave by S. Kempe, I. Bauer and H.-V. Henschel in 2001 and 2002. In 2002, the sump, so far separating the two caves, was explored physically by H.-V. Henschel, S. Kempe, and M.S. Werner, linking the survey of the two caves. The story of the discovery of these caves is related in Werner *et al.* (2002). Initial reports were given in Kempe, 2000; and Kempe *et al.*, 2001. In June 2002 we also learned that Dr. Fred Stone of the University of Hawai'i, Hilo, had investigated ThatCave biologically in 1992 (Stone 1992). He had named the cave Kuka'iau Piping Cave. Since older names take precedence, we changed the name of the cave to Kuka'iau Cave, dropping "piping", because the cave name should not give an interpretation of the mechanism of its formation. We also learned that Stearns and Macdonald (1946) mention the cave (p. 244): "A large lava tube 2.3 miles S. 10°W (longitude obviously in error, note of S.K.) of Kuka'iau Post Office constitutes an unusual source of water. Half a mile south of this point a stream disappears underground, apparently flowing

Table 1. GPS locations of Kuka'iau Cave entrances (map datum: Hawaiian):

Date: 04.03.01	North	West	Altitude a.s.l.
ThisCave Entrance	20°00,033'N	155°21,316'W	740 m
ThisCave Pit	19°59,972'N	155°21,317'W	746 m
ThatCave St. 1 (post)	19°59,617'N	155°21,387'W	869 m
ThatCave St. 4	19°59,637'N	155°21,398'W	843 m
ThisCave to Pit	Distance: 111 m	Bearing: 180°N	Vertical: 6 m
ThatCave 1 to ThisCave E.	Distance: 780 m	Bearing: 9°N	Vertical: 103 m
ThatCave 4 to ThisCave E.	Distance: 748 m	Bearing: 10°N	Vertical: 97 m

into the tube. During heavy rains a large stream of water emerges from the lower end of the tube, but it does not flow in dry weather. A large body of water remains in the tube, however, and is used to supply cattle tanks. About 50,000 gallons is siphoned from the tube every two months, but the tube never has been emptied." This citation explains the presence of bent and rusted pipes in ThisCave and of a well head above the sump in ThisCave.

LOCATION AND GEOLOGICAL SETTING

The Kuka'iau Cave is located on the north-eastern flank of Mauna Kea (Hamakua Coast), south of Kuka'iau (Fig. 1). We obtained valid GPS locations for the three entrances (Silva Multinavigator) (Table 1).

The location indicates (pers. com. Dr. Frank Truesdale, Hawaiian Volcano Observatory, USGS) that the cave is situated in the Hamakua Volcanics. These are the oldest volcanic rocks exposed on the Mauna Kea (Wolfe *et al.* 1997). They are dated to between 200-250 to 65-70 ka BP and consist mostly of alkalic and transitional basalts. In the upper part of the volcano glacial deposits are found as well.

The cave offers an excellent opportunity to study the structure of the upper Hamakua Series. It contains aa rubble and aa core layers as well as thick series of tubiferous (tube-bearing) pahoehoe, surface pahoehoe (with ropy surface structures), diamict layers (a layer of mixed rock sizes in a finer matrix of unclear genesis) and soil layers. The rocks are generally very weathered and have lost much of their original brittleness. All in all one can differentiate five units exposed in the cave. These are (from mauka to makai):

1. The Entrance Pit Series (pahoehoe, soils, aa rubble and core layer);
2. the Entrance Hall Series (a thick series of aa rubble and core layers);
3. the Vadose Stream Series (several aa rubble and core layers, paleosol / red Marker Layer, tubiferous pahoehoe and surface pahoehoe);
4. the Sump Series (pahoehoe sealed by halloysite); and
5. the ThisCave Series (overlying the Sump Series, consisting of a soil, an aa, and a diamict layer, and a thick aa core, which serves as the roof of ThisCave).

² mauka = Polynesian for "towards the mountain" i.e., upslope

Table 2. Survey statistics for the Kuka'iau Cave, separate for the ThisCave and ThatCave Sections, as of June 2002 (St. = survey station, see Fig. 2).

Measurement	ThisCave	ThatCave
1 Total added survey lines	272.1 m	1064.7 m
2 Total cave length (survey lines)	198.6 m	942.5 m
3 Total main passage survey	186.9 m	719.0 m
4 Total side passages (see below)	14 m	153.0 m
5 Total cave length (3+4)	200.9	872.0m
6 Total main passage length horizontal	184.5 m	704.7 m
7 Total main passage length horizontal (measured along center of passage)	160 m	679 m
8 End-to-end distance	132.5 m	572 m
8a End-to-end distance total (not the sum of line 8)		716 m
9 End-to-end direction (magnetic)	354°N	2.7° N
9a Total		(St. 1-23A*) 1.4° N
10 Sinuosity of total cave (horizontal)	-	(dripline to dripline) 1.17
11 Total altitude difference in caves	+1.3 m	((160+679)/716) -87.3m
11a Total altitude difference entrance to exit	(St.6-23)	(St.12-75) -85.4 m
12 Total altitude difference		-104.8 m
13 Entrance canyon vertical difference		(St. 5-75) -17.42 m
14 Maximal pressure above sump		(St. 5-12) 65 m = 6.5 bar
15 Average slope of main passage (St.12-60)		9.4°
16 Average slope of main passage (St.12-75)		($\tan^{-1}(77/464)$) 6.9°
		($\tan^{-1}(87/719)$)

*23A = Station 23A in ThisCave

The total of all surveyed and unsurveyed but explored side passages in ThatCave is:

A) At Station 23, Sand Tube:	31.8 m
B) At Station 24:	5 m
C) Stations 31-35: (- 4 m St. 31-32)	42 m
D) At Station 41:	5 m
E) Station 47 to 47C	26.8 m
F) Side passage between St. 53 and 56	40 m (not surveyed, horiz. estimate)
G) Station 77-78 (*0.5)	2.40 m
Total side passages	153.0 m (line 4 in Table)

MORPHOLOGY OF KUKA'IAU CAVE

GENERAL DESCRIPTION AND SURVEY DATA

Kuka'iau Cave consists in essence of one continuous underground stream passage (Fig. 2), directed mostly S-N. It has an upper entrance (a series of waterfalls in the gully of an intermittent stream) and a lower exit (a portal at the head of another gully, pirating the water from its neighbor). Only one other entrance is present, a 5 m deep pit at the upper end of ThisCave, possibly dug by the local ranchers to gain access to the water supply of the head sump for cattle (Stearns & Macdonald 1946).

This sump separates the two cave sections. We had to wait for two years before the water fell low enough to wade through the sump section and to tie the two surveys together (07.06.02). Compared to the GPS locations the survey was in error for 3.8 m in the N-S direction (mostly the tape and inclination error) and for 15.5 m in the E-W direction (mostly the compass error). Total main passage length of ThatCave is

719 m and of ThisCave is 187 m. The total cave length adds up to 1073 m (inclusive of some unmapped side passages see Table 1, Lines 3 and 4). Not many side passages exist (14 m in ThisCave and 153 m in ThatCave). The ratio between the main passage and the side passages is 5.2. The total vertical extent, according to our survey, is 105 m (for details see Table 2). For comparison, the vertical GPS difference between St. 4 (in the creek of the upper entrance) and the exit of ThisCave is 97 m (see Table 1), to which one has to add the drop from the roof of the cave (where the GPS measurement was obtained) to the floor of the stream bed which is ca. 6 m, yielding a very good correspondence between the GPS altitude difference and our underground survey. The slope of ThatCave is 6.9°. It is, however, steeper in the upper part of the cave. The sinuosity of the cave is 1.17.

GENERAL MORPHOLOGY

The importance of the cave system rests on the fact that the morphology of the cave is almost entirely determined by erosional features. The cave has morphologically four sections (compare Fig. 2):

- the unroofed entrances waterfall series, comprised of three up to 6 m tall water falls, water fall pools, steep and partly overhanging walls and a prominent meander;

- the steep, vadose underground stream course, mostly of a rectangular cross-section, dominated by water falls, water fall ponds, polished and scalloped rock bed chutes, rounded boulders and gravel chutes, undercut water fall lips, undercut walls and polished and scalloped walls;

- the level and even upward sloping phreatic sump section, mostly of an oval cross-section, showing several right angle bends and dominated by polished and scalloped floors, walls and ceilings, gravel banks and steep upward gravel and rock chutes;

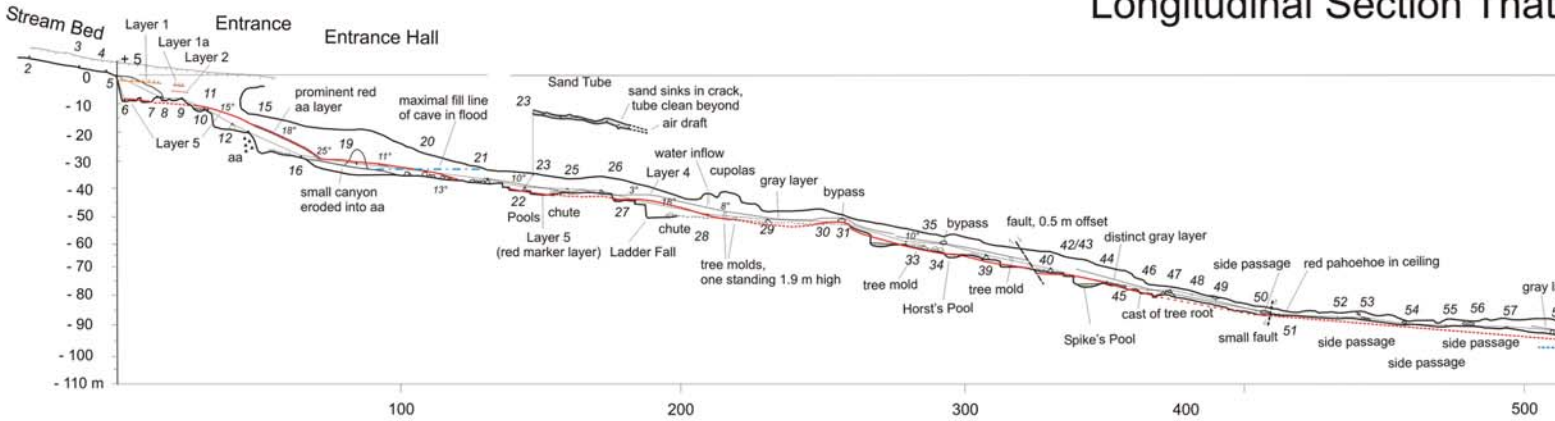
- the gently inclined vadose underground stream passage of ThisCave, of a wide rectangular cross-section, with only a few cascades, polished and scalloped rock chutes and a bed of large, rounded boulders and gravel.

Regarding side passages, two types have to be discerned: a very tight distributary side passage in ThisCave, which has been carved out at the interface between the underlying pahoehoe and the diamict, and those being most probably small lava tubes in origin (all the side passages in ThatCave).

These latter side passages partly form oxbows and cut-arounds, feeding back into the main cave and either serving as high water bypasses or forming blind appendices blocked by lava fills or collapses either mauka or makai. In these side passages, some of the features of small lava tubes are preserved, such as accretionary linings, glazing, and rarely stumps of lava stalactites and stalagmites. For example, the cave crosses a filled lava tube with recognizable linings between St. 51 and 52. At the beginning of the high water bypass at St. 32 there is glazing preserved at both sides of the entrance. In the cupola at St. 28 there may be an open tube crossing high up in the wall, out of which water seeps into the

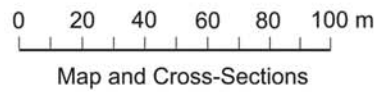
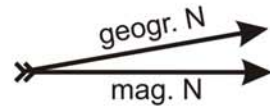
Kukaiau Cave (ThisCave and

Longitudinal Section That



ThatCave Mauna Kea Hamakua Series Lavas

surveyed:
R. and J. Elhard, H. - V. Henschel,
S. Kempe, P. Stankiewicz, M. S. Werner
March 31st, April 22nd, May 5th, 2000
June 7th and 9th, 2002
Geology: S. Kempe, I. Bauer
March 17th and 24th, 2001



Total Length	
Surveyed Mainpas	1
Main	4
Sump	7
ThisCave	2
Total Main	2
Surveyed Sidepas	23
Sand Tube	3
Sidepassage	4
Sidepassage	4
Sidepassage	1
ThisCave	2
Total Side	2
Total Main	2
Total Side	2

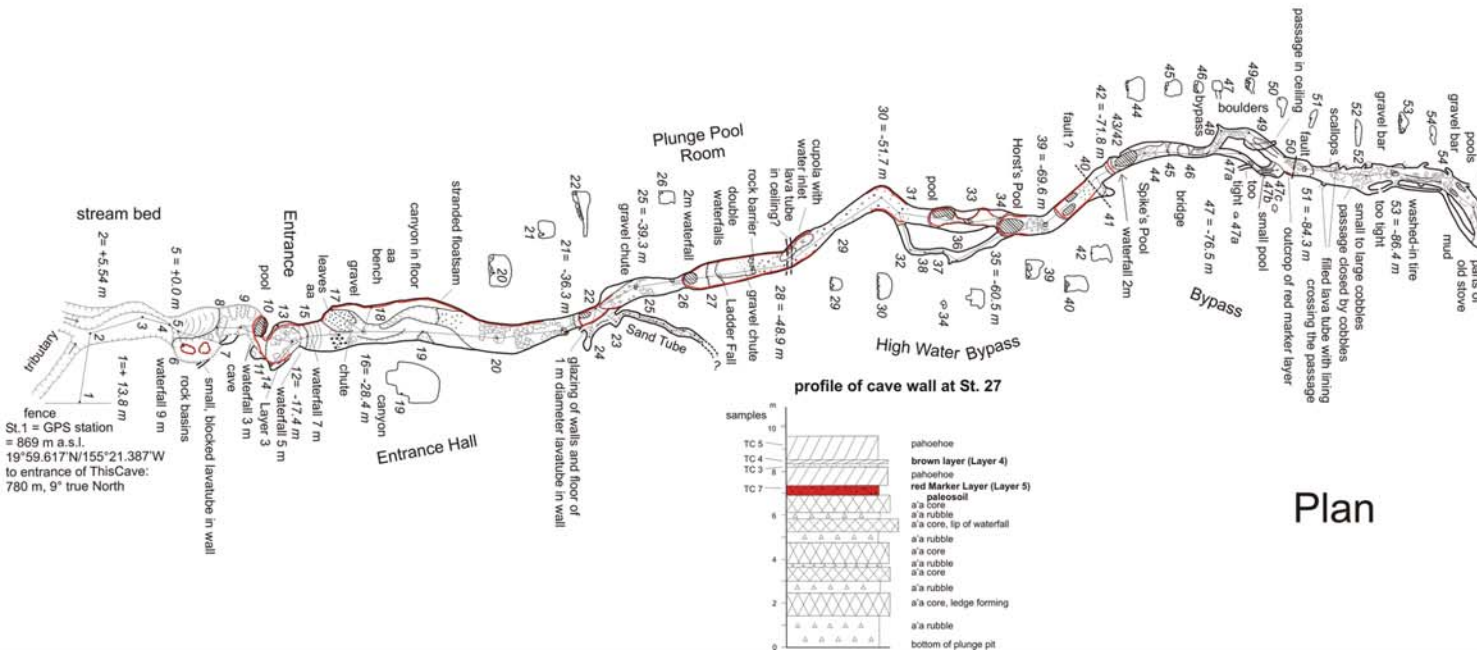
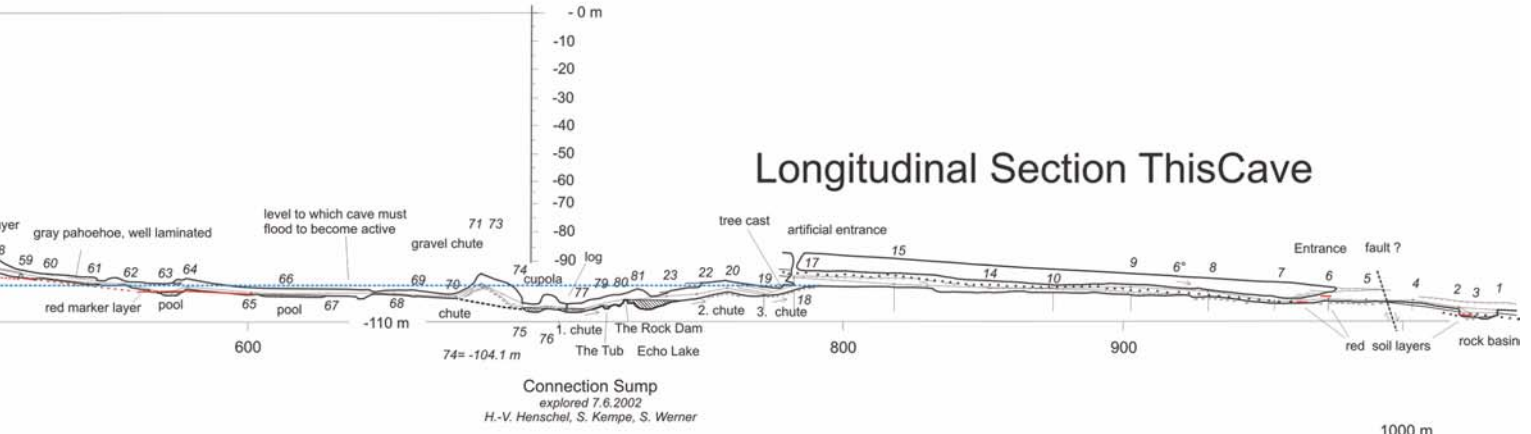


Figure 2. Map of ThatCave/ThisCave System. Note that the longitudinal Section has a slightly smaller scale than map and profiles. I

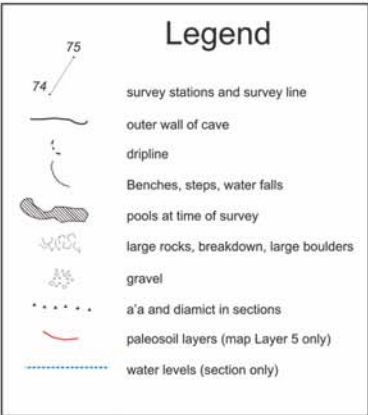
ThatCave), Mauna Kea, Hawai'i

Cave

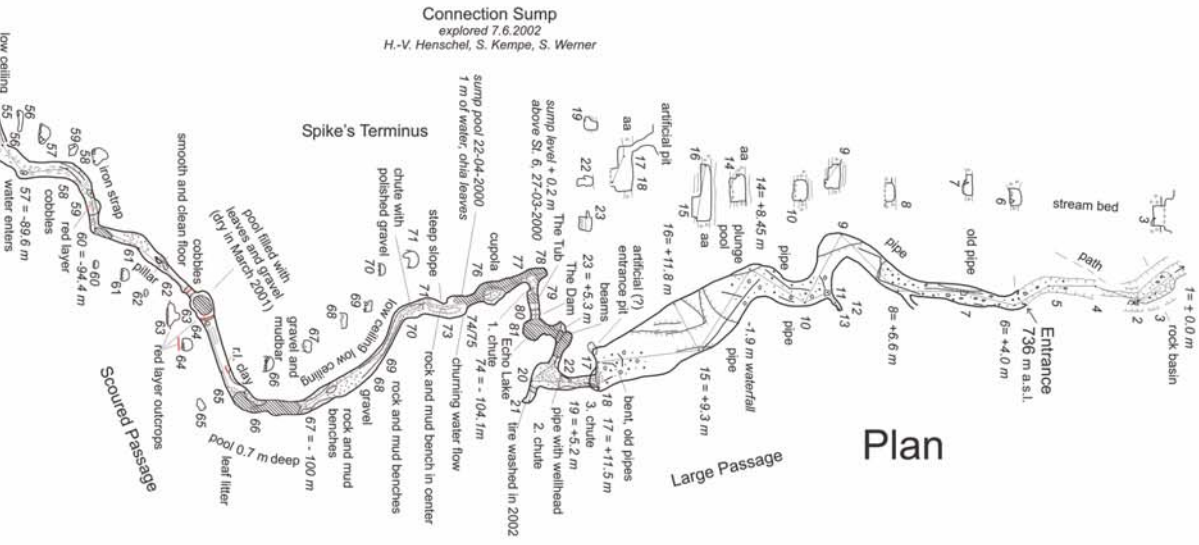


1000 m

Message	m	m hor.	m vert.	
2	42	305,35	298,34	-54,38
2	71	347,6	342,78	-24,77
1	23A	66,7	63,62	-5,76
6	23	186,96	184,51	-1,33
3	23A			0,8
		906,61	889,25	-85,44
Messages				
A	23G	31,8	31,2	
	24	5	5	
1	38	45,99	45,68	
7	55	27,2	26,77	
1	13	5,8	5,8	
0	21	5,9	5,39	
		121,69	119,84	
		906,61	889,25	-85,44
		121,69	119,84	

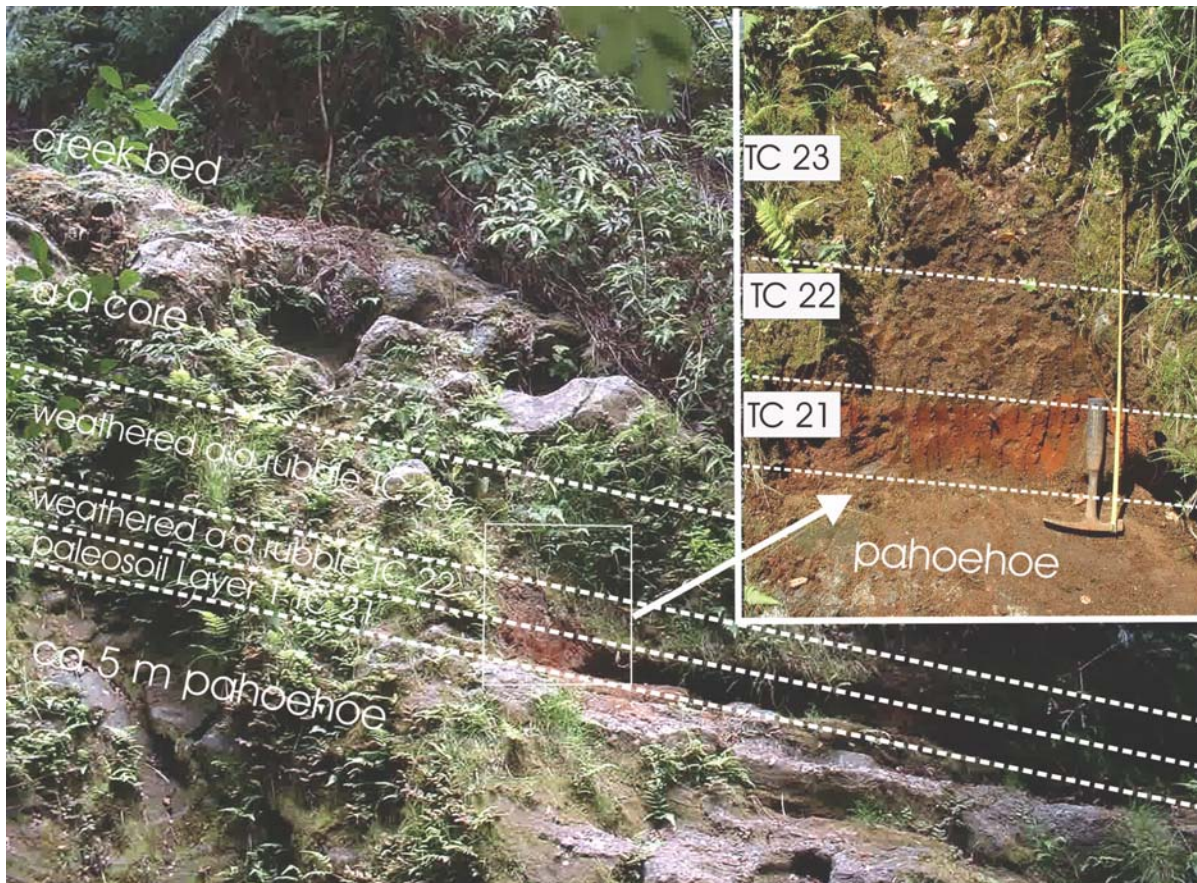


ThisCave
surveyed: S. Kempe,
H.-V. Henschel, P. Stankiewicz
March 27th, 2000



Drawn by S. Kempe.

Figure 3. Geological situation at the lip of the first water fall at the mauka entrance to Kuka'iau cave. The underlying pahoehoe is superseded by the quartz-bearing soil Layer 1 and covered by an aa flow. Its rubble is highly weathered and the core forms the present creek bed (lettering refers to XRD analyses given in Table 3).



cave. Also Dr. W.R. Halliday noted during a visit in February 2002 a piece of upward facing glazing on the eastern wall near St. 22. He collected a sample which he kindly forwarded to the authors together with on-site photographs. The sample plus the pictures and a site inspection in June 2002 shows that a filled lava tube has been eroded into sideward. The piece of glazing is part of a former lava tube representing the upper surface of a bench or ledge, from the left-hand side of a tube (left-hand looking makai). This is concluded from the fact that the specimen submitted has a wedge-like rim, which could be a flow line. This wedge-like rim is directed towards the present day wall, showing - as explained above - that the present cave has cut with its right-hand (eastern) wall through the left-hand (western) wall of a former, completely filled lava tube. The former floor of this ca. 1 m high lava tube is directed into the main cave and appears to form a prominent ledge. Where this small tube leaves the main cave could not be verified. Above this site, another small lava tube, albeit obliterated by breakdown, causes a widening of the main cave. This tube (Sandy Tube) departs from the same wall a few meters makai and was followed for ca. 30 m before becoming too tight. All these examples show that part of the vadose section of the cave was eroded into a stack of tubiferous pahoehoe, featuring several smaller tubes on top of each other.

Other features, which could be mistaken for lava tube formations such as structures similar to lava falls or flow lines are present throughout the cave. Upon closer inspection, none

Kukaiau Cave (ThatCave)
profile of cave wall at St. 27

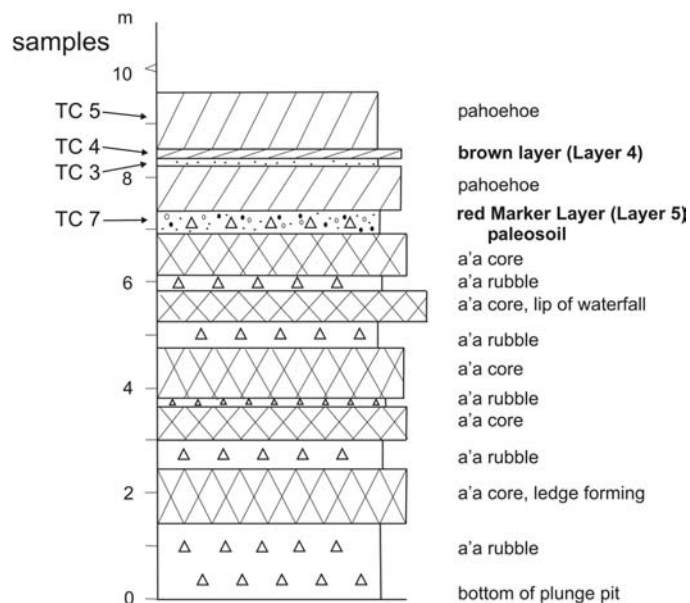


Figure 4. Stratigraphic section exposed in Kuka'iau Cave at the plunge-pool series near Station 27 (sample numbers refer to XRD analyses given in Table 3).



Figure 5. The connection sump: (A) view makai at the Rock Dam holding back Echo Lake. Note the notch cut by water overflowing the Rock Dam back into the deeper part of the sump (where person is standing). (B) View from the crest of the Rock Dam, across Echo Lake into the lower part of ThisCave (person at St. 23A). Even when the sump is dry, Echo Lake is kept flooded because of the halloysite filling all the interstices of the rock in this section of the cave. (C) As the water rises out of Echo Lake it has to move up this gravel chute into the Wellhead Room. Note size of gravel (up to 10 cm in diameter) being moved uphill makai by water when the cave floods. (D) View mauka, down the last gravel chute. Person stands at the makai end of the Wellhead Room. Here the water rises from the sump to overflow into the vadose stream passage in ThisCave. Note the size of the gravel and stones being moved up this steep gravel chute. Pictures by S. Kempe.

of these features are, however, lava tube-related, rather they represent exposed aa blocks or differentially eroded sheeted lava flows.

The typical morphological elements of larger lava-tube systems (reviewed, for example, in Kempe 2002; compare also Allred 1997; Greeley *et al.* 1997; Kempe 1997) are however missing. These include large tributary branches, primary tubes near the ceiling of the tube, wide halls being eroded underneath deep lava falls, secondary ceilings which separate deeply eroded canyons into two or more passages, remains of welded breakdown and others. Furthermore, the large change in the gradient of the cave is atypical for lava tubes, and upward gradients have never been documented.

On the mesoscale the absence of accretionary linings, lava falls (which would have been eroded anyway) and lava-tube floor formations such as tube-in-tube structures and others should be noted. On a smaller scale, flow features along floor, ceiling and walls (e.g., levees, accretionary ledges, lava balls, glazed surfaces, stalactites and stalagmites, runners and drip piles) or any other features caused by molten lava and associated with lava tube formation are not seen.

Kukaiau Cave (ThisCave)

Profile of rock strata mauka end at stations 18, 19

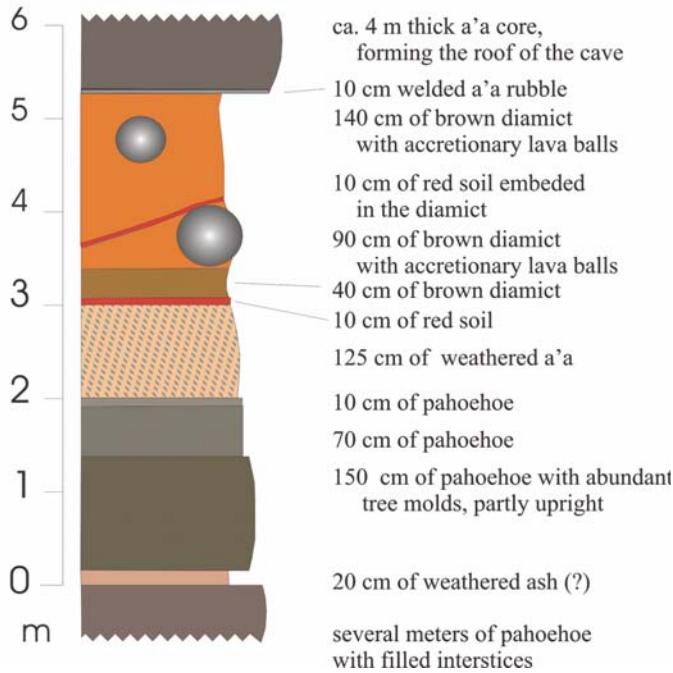


Figure 6. Geological profile of the ThisCave Series at the head of the Large Passage in ThisCave.

Profile at Entrance to ThisCave (W-Wall)

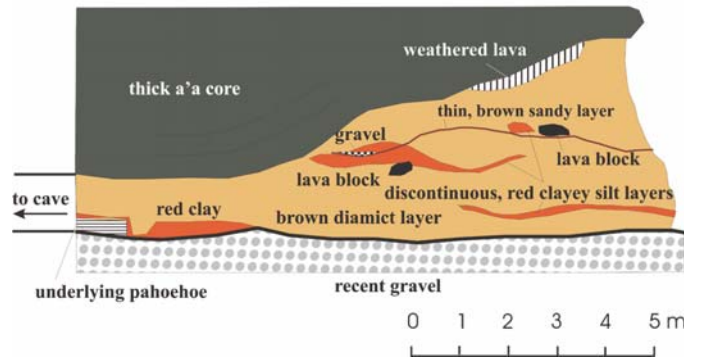


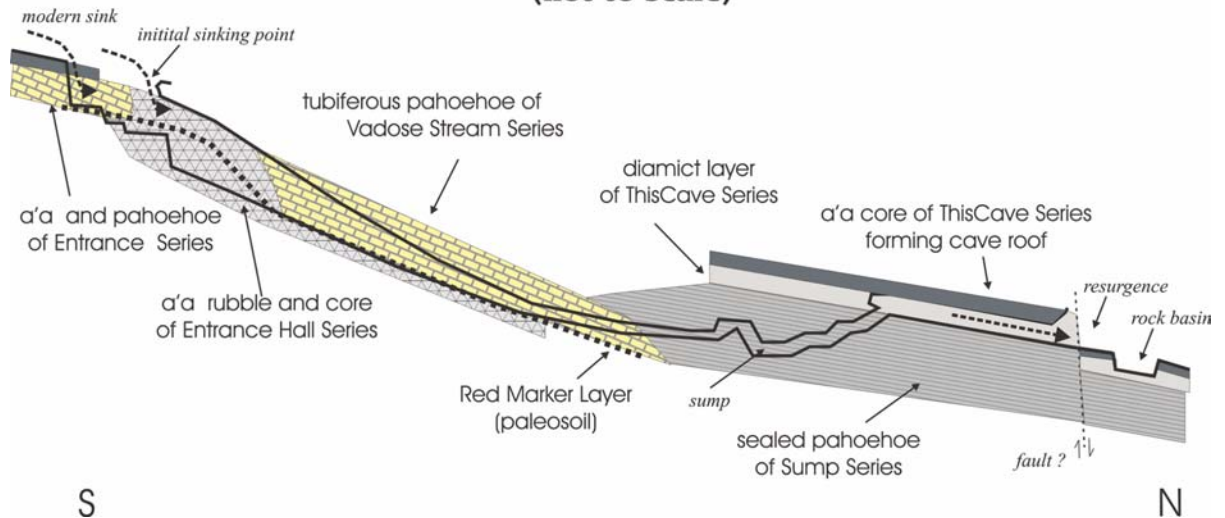
Figure 7. Geological profile of the ThisCave Series at eastern wall of the resurgence.

The morphological elements of an erosional origin are, on the other hand, ubiquitous. The cave floor is either composed of solid rock sculptured by stream pots, chutes or scallops, or it consists of beds of rounded boulders, cobbles, or gravel. Garbage, plant residue, and parts of trees are found throughout the cave, testifying to its function as a recent water course as well. Farther down, where the passage narrows, one finds Styrofoam debris wedged into cracks in the ceiling by high water. The solid-rock sections include waterfalls with water fall lips, undercut waterfall walls and large plunge pools. The gravel sections include gravel chutes, leading upward and out of plunge pools, boulder jams, behind which gravel is impounded, and older gravel banks are consolidated by mud (in the lower part of the cave).

The walls of the cave are either stream worn (in their lower reaches) or show bare, joint-controlled faces making visible the bedrock through which the cave has cut. The ceiling is shaped either by breakdown, exposing horizontal and planar

Figure 8. Schematic longitudinal section through Kuka'iau Cave with the most important geological units.

Schematic Geological Section through Kukaiau Cave (not to scale)



lava partings such as aa core – aa rubble interfaces, pahoehoe surface roping or pahoehoe sheet separations. In a few constrictions of the lower reaches of the cave and in the sump section, the ceiling also shows marks of erosive action.

The cross-sections of the cave vary from wide canyons, to narrow canyons, from rectangular habitus to a more oval shape. In the main passage, they appear more to be determined by breakdown enlargement rather than by down-cutting.

A WALK THROUGH THE CAVE

The episodic surface stream, which feeds the cave, runs on top of an aa core (in Hawaii called “blue rock”) that shows vertical, wide-spaced, irregular columnar contraction joints. At Station 5 (St. 5) of our survey this layer is breached and the stream plunges down into a pit 6 m deep with two plunge pools at the bottom. This and the two successive water falls, which lead down to the cave entrance, constitute the impressive entrance series. All water falls could be bypassed or free climbed. On the walls various steeply sloping layers of loose brownish or reddish paleosoils are exposed (Layers 1, 1a, 2 and 5 marked in the Longitudinal Section, Fig. 2) (Fig. 3). Vegetation and moss make it difficult to follow these layers entirely. Layer 5 can be traced from the bottom of the two plunge pools of the first water fall to the foot of the second water fall and along both sides of the widening below the last of the three water falls, where it dips makai with 15°. Then one stands in the gaping, 6.5 m high and 3 m wide, mouth of the cave. Inside is another waterfall to be climbed down. It exposes a thick layer of aa rubble, only partly consolidated by fine-grained matrix and interspersed core layers making climbing down the 6 m step easy and dangerous at the same time since the abundant hand- and footholds can readily break off. To the right, solid rock occurs and here the water normally plunges down, having carved chutes. To the left, aa rubble and thin, ledge-forming and steeply inclined (at first sloping at 18° then at 25°) aa core layers compose the wall. The aa rubble must belong to at least two different flows since the redbrown paleosol Layer 5 (termed Marker Layer) can be followed from the entrance high up in the wall. The lower aa rubble could represent a lateral levee of a large aa flow, the core of which now forms the right-hand wall. The core layer is vertically jointed (either tectonically or through contraction) and can easily be mistaken as the remains of a thick lining.

The Entrance Hall is the largest room in the cave, 10 to 12 m high and 8 to 11 m wide. The plunge pit is filled with leaves and tree trunks. Some large blocks from the aa bench litter the floor. A chute with large, rounded blocks leads to a steeply dipping solid platform (one of the blue rock layers) into which a small canyon is cut. It is partly covered by large breakdown blocks. The passage declines less steeply than the layering of the rocks and the prominent red Marker Layer exposed on the left wall meets the floor at about 70 m below the entrance (Layer 5) for the first time.

This layer apparently played an important role for the genesis of the cave, because it will be seen again and again up

to St. 65 either along the walls of the cave or at the base of plunge pools. The solid lava sheet above it very often forms the floor of the cave, sculptured by the running water. Above this solid-lava layer is found another important layer, Layer 4. It is composed of bedded but very weathered brown or gray material. It can also be traced down to at least St. 59 and appears to be the parting from which this section of the cave originated. Consequently, from St. 21 onward, the cave follows the local inclination of the strata which is actually highly variable as indicated in the Longitudinal Section in Fig. 2.

Between St. 19 and 20, below the left wall, flotsam, composed of plastic bottles, plastic parts, sandals, wood, and the like is concentrated. Water apparently ponds up to this level when the cave floods. This conclusion is substantiated by the observation that the walls below this point appear clean-washed while the walls of the upper Entrance Hall are encrusted with dust.

Below St. 21, the cave widens as several small lava tubes are intersected as described above. The upper one leads mauka to a collapsed room, but can be penetrated for more than 30 m makai. At first it is floored by muddy sand, which shows that at high water the tube is also inundated. There are no signs of erosion though. Towards the end, the sand disappears, presumably washed into a crack in the floor and the tube continues as a pristine small lava conduit. There is an air draft, indicating that the tube does not end blindly, it is however too small to be easily followed further.

At St. 26, the Plunge Pool Room opens up, offering the most detailed view into the strata below the red Marker Layer and an almost ten meter-high section of lava sheets and intermittent aa layers can be studied (Fig. 4 and inset in Map of Fig. 2). Further makai, the floor levels off as the red Marker Layer descends down to the floor. Above, breakdown cupolas open up to a height of 8 m. From one of them water seeps down, possibly from an open lava tube intercepted at the ceiling by breakdown.

Beyond a prominent bend in the cave at St. 31, the first high-water bypass opens up, a small lava tube developed at the level of Layer 4. Its floor also forms the floor of the main tube i.e. the lava sheet above the red Marker Layer. It is the base of the stack of tubiferous pahoehoe. This sheet is relatively dense and hard, showing that it was quickly cooled. Above it several other sheets occur, on first inspection more vesicular and possibly less quickly cooled. The next one up is the one in which the small lava tube is situated. This layer could therefore have been inserted between the base sheet and the next one up, thereby forming a hot core in the inflating lava flow (for the concept of how primary lava conduits form at the tip of tube-fed pahoehoe flows compare Kauahikaua *et al.* 1998). The hot core is the site where the proto-tubes form, often in parallel to each other. The branching-off of the side passage suggests that there may have been a small tube also within the main passage mauka. There are remains of glazing on the right wall of the main passage immediately below the branching, therefore a

small tube may also have continued down the main passage.

A little further makai, the base sheet of the tubiferous flow has been cut through by the erosion of the stream, exposing the red Marker Layer, lining the sides of the plunge pool below. A small canyon, formed by the protruding ledges of the base sheet of the pahoehoe flow, forms the lower part of the main passage. Here molds of trees, encased by the base sheet are exposed. They illustrate that the Marker Layer is in fact a paleosoil, which carried a forest.

At the lower intersection with the bypass, a large pool is situated (Horst's Pool, named in honor of Horst-Volker Henschel who took a plunge in it when one of the handholds of the lateral traverse came loose).

Mauka of St. 40, a fault is crossed, down-faulted makai. Then Spike's Pool is encountered, below a 2 m high waterfall. It is the best example of a deep, wall-to-wall pool. Seemingly not climbable, Spike Werner found a way around it, needing to follow one of the lower aa layers beneath the lip of the water fall along the right wall. Below St. 47 (at a depth of 76.5 m below the first waterfall in the entrance), several more lava tube-bypasses occur on the right-hand side and the cave becomes somewhat smaller and less steep. At St. 50, before a small fault at which the mauka side is down-faulted, the red layer reappears once more. Below St. 51, a filled lava tube is cut through, as already mentioned. In this section the exposed pahoehoe is rather thin-sheeted and bears rope marks typical of pahoehoe solidified at the surface. Makai more small tubes enter and leave the main passage at various levels. The cave now is considerably lower than before and has more the appearance of a phreatic tube than that of a canyon. The floor consists of gravel.

The clean-washed floor reappears before St. 62, where the cave narrows once more. This is the section which best resembles the appearance of a lava tube. Since we have been this low in the cave only twice (due to the high risk of being caught by a sudden storm discharge) there is not enough information to assure that this section of the cave is also structurally a lava tube. Below this constriction (2*1.5 m) the cave opens up once more into a larger plunge pool room. Again the red Marker Layer is seen along the perimeter of the pool below the waterfall lip. In spite of the otherwise wetter conditions (compared to the spring of 2000), this pool was empty in March 2001 (except for a thick deposit of decaying leaves), suggesting that the water can escape into a deeper groundwater body by means of the various aa layers underlying the tubiferous pahoehoe. One has to climb upward and out of the pool at the makai end, unlike the end of the previous pools which terminate mostly in gravel chutes. This raises the question where the material eroded from the pool was transported. The passage beyond is horizontal and floored with sandy mud. In April 2000, it was dry, but in March 2001 it was filled with water from a previous flood in the cave and sumped at around St. 68, so that the terminal sump could not be reached.

From here on, no remains of small tubes have been noticed, the cave moves through a tightly sealed stack of pahoehoe sheets. The "terminal sump" was reached first by M.S. Werner and R. Elhard in May 2000. On June 7th 2002 we entered the makai entrance when exploring the sump section and investigated it geologically on a trip through the entire cave on June 23rd. The passage leading toward it has the most unusual form: First it rises up by 5 m and then becomes very low because of gravel being transported up a chute; it then plunges down by 7 m to a terminal pond filled with murky brown water (in May 2000). Solid mud banks with cobbles line the passage, and these have more recently been cut and partially removed. Overall, the hall above the sump gives an impression of how the water churns when at full flow.

In summer 2002 the water level fell about a meter below its stand in May 2000, making the sump accessible. Still one has to wade and in Echo Lake one is up to the belly in the water. From the terminal sump the passage is level, much deeper on the left than on the right side. It ends blindly at St. 78. A gravel bank leads into the continuing passage which makes a sharp right turn. Here the upward rising rock floor is encountered again. A large stream pot, "The Tub", interrupts the floor. Beyond, a solid Rock Dam bars the passage, damming "Echo Lake" from flowing back mauka into the sump. This is the most unusual feature in the cave, difficult to envisage even when described. There is even a small channel incised into the dam, through which the water of Echo Lake trickles backward into the lower-lying but dry sump. The crest of the Rock Dam is horizontal, in level with Echo Lake. The lake is about 8 m across and over 2 m deep at the far side and a sizeable cupola helps to reflect the sound giving the lake its name. The Rock Dam prevents the water level from falling lower, the level is therefore no indicator if the sump mauka of the lake is passable or not. We only understood that the sump opened up because of a pulsating air flow.

The passage makes another sharp turn to the left and one emerges from the lake into the lower part of ThisCave where the passage turns right again (Fig. 5). A few logs rest on the lake floor. At S. 23A the two surveys were tied together. The floor of the passage rises out of the water and meets a steep gravel chute leading upward into the Well Head Room. On the far side there is a blind appendix again, carved out by the water jet churning around. Here we found in June 2002 a truck tire resting on our survey St. 21. It must have passed the cave during a flood in the winter 2001/2002. The passage makes one last left-hand turn and another gravel chute leads steeply upward into the vadose passage of ThisCave, breaking through the top of the pahoehoe Sump Unit. This unit is characterized by the absence of any open space in the rock package: All bedding planes, all contraction cracks and the vesicles of the rock are filled with a white, waxy material, thereby effectively sealing the rock. Due to this compact wall surface, scalloped on ceiling, walls and floors, the passages reverberate with sound, similar to the acoustic perception of limestone caves. None of the wall sections inspected revealed any lava tube

Table 3. A) Semi-quantitative results of X-ray-diffraction analyses of rock samples (analyses courtesy of R. Apfelbach, Darmstadt). Percent concentrations were estimated according to the reflex intensity as compared to known standards. Percentages refer to X-ray active minerals only where there is a large amorphous fraction. In the samples with small amorphous fractions the amorphous fraction was estimated as well. As an example the results of samples TC-21 to TC 23 are given in both notations, simple numbers denote overall composition, numbers in brackets denote composition of the crystalline fraction only. Sample ThatCave 3 was analyzed for various grain size fractions.

Sample	Color of ground sample	Plagioclase	Augite	Olivine	Hematite	Others	Rest
Samples collected Aug. 2000 between St. 25 and 27 by M.S. Werner and W.R. Halliday							
ThatCave 1, Gray, vesicular (2-3 mm) lava, white pore fillings	Light gray	25%	24%	42%			9% amorphous
ThatCave 2a. Brown, vesicular (ca. 1mm) lava	Dark brown	7%	58%	-	4%	5% meta-halloysite	26% amorphous
ThatCave 2b brown mud on surface of 2a	Brown	-	43%		5%		50% amorphous
ThatCave 3a (3=red Marker Layer) coarse component	Reddish brown	-	48%		14%		28% amorphous
ThatCave 3b Green shards of augite clasts	Light greenish gray	-	96%				amorphous
That Cave 3c fine-grained components	Reddish brown lighter than 3a)	14%	52%	-	12%	5% meta-halloysite	17% amorphous
That Cave 3c fine-grained components (< 2 μ)	Reddish brown	13% (forsterite)	53%	6%	17%	11% meta-halloysite	Some amorphous
March 2001							
TC 1 surface between This- and ThatCave, yellowish weathered rock	Light gray	64%	23%	10%	-	3% Magnetite	
TC3, Profile St. 26-27 Layer 4! (10cm crumbly rock)	Light brown	14%	36%	47%	3%		
TC4, ProfileSt.26-27 above Layer 4 (13 cm harder layer)	Light gray, brownish	21%	36%	40%	3%		
TC5, Profile St. 26-27 above Layer 4(1 m crumbly rock)	Light gray	26%	45%	27%	2%		Large X-ray amorphous component
TC 6, Layer 4 St. 31 begin of bypass	Light gray-brownish	22%	53%	14%	5%	Halloysite: 6%	Large X-ray amorphous component
TC 7, Red Layer, Layer 5, makai St. 31	Light gray brownish	16%	28%	19%	29%	8% undeterminable	Large X-ray amorphous component
TC 9, Lava from wall, above St. 42, large white spec in pores	Brownish	23%	48%	13%	11%	5% undeterminable	Large X-ray amorphous component
TC 10, layer 1 at St. 7	Light brown red	12%	48%	13%	45%		Large X-ray amorphous component
TC 11, layer 1a at St. 9	Brown red	-	-	-	37%	Quartz! 19% Donathite* 44%	Very large X-ray amorphous component
TC 12. Layer 2, at St. 9	Dark gray brown	-	15%	41%	22%	Illite 18% 4% undeterminable	Very large X-ray amorphous component
TC 14, Layer 5 between St. 20 and 21	Brown-red	15%	45%	13%	22%	5% undeterminable	Very large X-ray amorphous component
TC 15, Layer 5, red Marker Layer at St. 23	Intensive brown-red	0%	39%	16%	39%	6% undeterminable	Large X-ray amorphous component
TC 16, solid lava above red Marker Layer at St. 22	Light gray	32%	39%	22%	0%	7% undeterminable	Medium X-ray amorphous component
June 2002							
TC 20 ThisCave, white waxy material sealing voids in Sump Pahoehoe Unit	Light grey	-	-	-	-	100% Halloysite	Large amorphous component
TC 21, Layer 1a at entrance to ThatCave, St. 5	Reddish brown	5% (15%)	-	-	5% (15%)	Quartz 11% (33%) Halloysite 5% (15%) Donathite 7% (21%)	67% amorphous
TC 22, weathered aa rubble above TC 21	Light brown	4%	-	-	-	Halloysite 18% (72%)	75% amorphous
TC 23, weathered aa rubble above TC 22	Dark brown	7%	-	-	-	Halloysite 18% (67%) Magnetite 2% (7%) *Donathite (Fe,Mg)(Cr,Fe) ₂ O ₄	73% amorphous

Note that samples from 2000 were dried at < 50°C transforming the halloysite into meta-halloysite.

Table 3. B) Results of carbon, nitrogen, sulfur (C, N, S) total elemental analyses of rock samples from ThatCave, results are given as weight percent.

Sample	C(total) %	C(inorg.) %	C(org.) %	Total org. matter %	N %	C/N	S %
ThatCave 2b brown mud on surface of 2a	3.67	0.33	3.34	8.35	0.43	7.8	1.19
That Cave 3c fine-grained components	0.04	0.00	0.04	0.1	0.11	0.36	0.76

Table 3. C) Results of porosity analysis of rock sample from ThatCave.

ThatCave 2a. Brown, vesicular (ca. 1 mm) lava	weight 43.804 g	Envelope volume 27.54 cm ³	Sample volume 13.78 cm ³	Density 3.178 g/cm ³	porosity 49.9%
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structure. The upward course of the passage, the fact that the ceiling of the passage jumps upward from sheet parting to sheet parting and the seemingly joint-controlled sharp turns of the passage exclude any possibility that a precursor lava tube has been enlarged by erosion in this section of the cave

Beyond the third and last chute the water boils upward into the rectangular vadose passage of ThisCave, which is up to 14 m wide. Light filters down through the pit in the corner to the left. From here on, the passage drops at about 6° to the stream resurgence less than 200 m away. On its way it winds through an S-shaped bend. The floor of the cave is formed by the sealed pahoehoe of the Sump Unit (Fig. 6). The last sheet carries many tree molds (best exposed at some of the cataracts), suggesting that there was a longer hiatus between the deposition of the bulk of the Sump Unit and the last flow covering it. Below the layer with the tree trunk a thin bed of soft material is found, possibly also a paleosoil. At places the water has eroded several meters into the top of the Sump Unit, forming cascades and showing scalloping and stream pots. The wide and flat roof is formed by the lower interface of a thick aa core layer. Only in a few places have blocks fallen out of the ceiling. They are the source of the large rounded blocks in the streambed. The walls are composed of a series of unconsolidated rocks (Fig. 6). There are two red paleosoil layers, one immediately on top of the pahoehoe Sump Series, an aa rubble layer and a thicker diamict layer on top. The diamict layer continues to the mouth of the cave. There it increases in thickness causing the blue rock ceiling to rise on the last few meters of the passage. On the left wall the diamict shows an interesting internal structure with discontinuous red soil layers incorporated in it (Fig. 7). It is this diamict layer which has been removed to create the cave. Certainly no precursor lava tube could have existed in this rock series. This section of the cave is entirely erosional in origin.

Outside of the cave's exit a cobble bank causes water to pond inside the entrance, forming a temporary lake. This temporary lake may have caused the ranchers to dig the artificial pit in order to gain access to the water in the sump at all times. From the mouth of the cave the stream flows first over gravel but then the blue rock of the cave roof is encountered again, possibly down-faulted by a small fault crossing the creek. A few meters makai the creek plunges into an impressive rock basin. There the diamict layer is exposed once more, featuring also a red soil layer.

PETROGRAPHIC DATA

In spite of the morphological clues speaking of an erosive origin for Kuka'iau Cave, it nevertheless is challenging to explain the origin of an erosive cave of such dimensions in lava layers which at least in part lack the advantage of a

precursor lava tube. In order to advance our understanding of the cave genesis we therefore took rock samples for mineralogical, petrographic and geochemical analysis in August 2000 (W.R. Halliday and M.S. Werner, designated "ThatCave 1 to 3"), March 2001 (S. Kempe and I. Bauer, labeled "TC 1 to 16") and in June 2002 (labeled "TC 20-23"). A subset of these samples was ground and X-ray-diffraction (XRD) analyses were conducted (Philips PW 1949 powder diffractometer, data evaluation according to the International Centre for Powder Diffraction Data). Additionally some thin sections were made and elemental carbon, nitrogen, and sulfur concentrations (CNS Analyzer Vario El, Elementar) were determined. Porosity was measured on one sample as well. All results are listed in Table 3.

The analytical results show four general types of composition: (i) samples with a general basaltic composition, (ii) samples with a high hematite content, (iii) samples with a composition unusual for Hawai'i, and (iv) samples with a high halloysite content.

The first group comprises the samples (ThatCave and TC1, 3, 4, 5, 6, 9, 16). They have high augite, olivine and plagioclase contents; hematite may be present in small quantities. These samples are gray or gray with a brownish hue in color and represent the solid lava samples composed of tholeiitic and alkalic basalt representing the Hamakua Volcanic Series of the Mauna Kea volcanic edifice. In thin section, the olivine is partly altered to iddingsite ($MgFe_2Si_3O_{10} \cdot 4H_2O$) or hematite (Fe_2O_3) which form along the cleavages of the olivine crystals.

The samples (ThatCave 3 and TC 7, 10, 14, 15) from the bright red brown, unconsolidated material of Layers 1 and 5 form the second group. They are also composed of augite, olivine, and plagioclase but have significantly higher hematite contents. These samples most probably represent paleosoils developed on weathered volcanics.

Samples TC 11, TC 12, and TC 21 belong to a third group. They represent unconsolidated, fine-grained material with a composition atypical of Hawaiian lava, i.e., with significant concentrations of quartz, donathite, and illite. Layer 1a, which contains quartz, donathite and hematite, is a soil layer containing continental (Asian) dust (the only known source of quartz for Hawaii). Under the ESEM (environmental scanning electron microscope) quartz particles were difficult to find since they are coated with hematite and amorphous Al-silicates. The few grains identified by EDX (energy dispersive analysis of X-rays) had a short, rounded, columnar form, 1-2 μ long. This habit would support the interpretation of continental dust as a source for the quartz. Layer 2 contains illite in addition to augite, olivine, and hematite. It again could be a paleosoil in which illite could be either a dust-born addition or a weathered equivalent of the plagioclase.

Sample TC 6 (Layer 4), 20, 22 and 23 – the fourth group of samples—have high contents of halloysite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \cdot 4\text{H}_2\text{O}$). In samples from March 2000 (Samples That Cave 2a, 3c) meta-halloysite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) was detected. It most probably originated from halloysite because the samples taken in 2000 were dried at higher temperatures. Halloysite is the only X-ray detectable component in the white, waxy material filling the voids in the Sump Series pahoehoe (Sample TC 20). Halloysite was also detected in several of the samples from Pa‘auhau Civil Defense Cave (see Kempe *et al.* 2003). Halloysite is a clay mineral which forms during weathering and is common in Hawaiian soils and weathered basaltic rocks (so called sapolite) (e.g., Patterson 1971; Vitousek *et al.* 1997).

To check if all of the white, waxy material in the vesicles of the lava is halloysite, we scraped some of it from the pores of rock sample TC 9 and X-rayed it. It proved to be amorphous. We then looked at this waxy material under the ESEM and analyzed its composition by EDX. It contains a variable amount of Al and Si; thus it could either be the amorphous forerunner of halloysite or represent the amorphous Al/Si phase called allophane ($(\text{Al}_2\text{O}_3)(\text{SiO}_2)_{1.3} \cdot 2.5\text{H}_2\text{O}$).

ESEM examination of a subsample from Layer 1a (the one with the quartz, TC 11 and TC 21) and Layer 2 (with illite, TC 12) showed that layered, amorphous Al-Si phases are ubiquitous in the paleosoils. They, together with the very fine-grained hematite mantle all the surfaces of other minerals almost completely. It is difficult to identify the other phases in the sample by EDX, and only the larger grains of weathered augite seem to be relatively clean. This, however, could be due to the fact that they easily break in sample preparation, producing fresh cleavage faces.

C-N-S data (Table 3b) show that the mud on the wall of the cave (sample ThatCave 2b) is eroded recent soil with a high organic C content (3.3 %) and a high C/N ratio (7.8 by weight). In contrast, the red Marker Layer (sample TC 3c) has very low C and N contents. This is either due to its older age or to the fact that the soil was baked by the transgressing pahoehoe sheets which oxidized all of the former soil matter.

CONCLUSIONS FROM THE MORPHOLOGICAL AND GEOLOGICAL OBSERVATIONS

The XRD data illustrate that the weathering of feldspars, olivine, and augite has created amorphous or poorly crystallized clays, i.e., halloysite and allophane. These accumulate in the voids of the rock, causing the rock layers to become less permeable. This in turn gives rise to a local perched water table. The more the sinking water is retarded, the more weathering will occur facilitating the final closing of vesicles and other interstices.

The geological observations in the cave allow us to identify two major impermeable layers: The paleosoil Layer 5, i.e. the red Marker Layer inclusive of the pahoehoe sheets immediately above it and the Sump Series pahoehoe. The

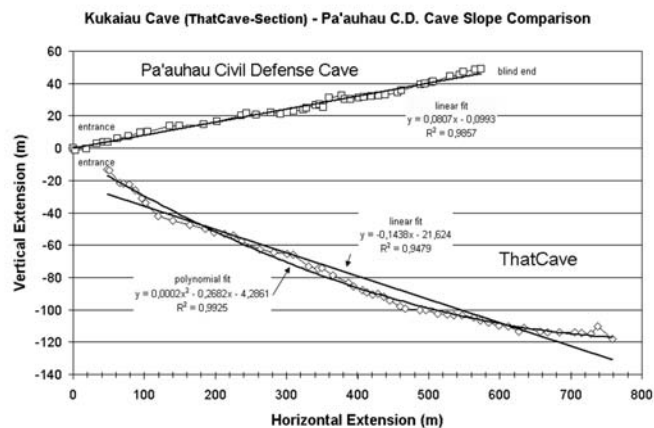


Figure 9. Comparison of the depth/length profile of ThatCave (erosional) and Pa‘auhau Civil Defense (lava tube).

paleosoil could have served as an initial water impediment to retard further vertical drainage and cause lateral groundwater flow in the small lava tubes above the base sheet and through the partings between these lava sheets. This alone however is not enough to form the cave.

A large hydrostatic pressure must be exerted as well. This was possible because Layer 5 runs through a highly porous aa rubble series near the entrance which was intercepted by a gully. This water could rapidly infiltrate through the aa, fill the voids in the stack of the tubiferous pahoehoe below and exert a pressure of almost 10 bar on the distal part of the groundwater body. This could have been enough pressure to force the water along orthogonal joints upward through the otherwise impermeable pahoehoe Sump Series into the overlying diamict. The diamict has a high porosity (no exact data yet available because the rock is very crumbly) and could conduct the water along its layer to a new exit, the present resurgence. In this way an erosive cave could have formed by a set of fortuitous geological circumstances at this site (Fig. 8). In this model it is not necessary to have a tubiferous pahoehoe as an initial water conductor. aa rubble or any other rock types of a high initial porosity would serve just as well. Therefore the cave is not just an eroded lava tube where a stream invaded at the mauka end and flowed out at the makai end (for an example of this type see the Pa‘auhau Civil Defense Cave, Kempe *et al.* 2003), but it is the product of a complex interaction between a perched water table and the structural components of the rock strata.

CONCLUSIONS DERIVED FROM CHANNEL MORPHOLOGY AND SOIL AGE FOR THE AGE OF THE SYSTEM

The morphology of bedrock channels is determined by substrate and hydraulics, (e.g., Wohl & Merritt 2001). According to Wohl (1998) the reach-scale morphology (i.e., the morphology of a section of the channel several times longer than its width) of Kuka‘iau Cave can be classified as a

single flow path, variable bed gradient channel, with a dominant step-pool morphology ("downstream bed undulations in form of vertical steps with pools between them"). The step-pool morphology is aided by the heterogeneity of the bedrock itself: lava layers are separated by layers of loose material which can be ash layers, paleosoil layers, aa rubble, or simply contact zones between pahoehoe sheets. Also, vertical contraction cracks and possibly faults play a role in bedrock strength in Kuka'iau Cave. Overall the bedrock is inhomogeneous, therefore aiding in the formation of a step-pool morphology.

Overall, the depth-length relation of the cave is best described by a polynomial fit (given in Fig. 9), consistent with a water-related origin. Groundwater tends to sink quickly toward the water table before flowing horizontally. In contrast, lava tubes follow the slope of the mountain and tend (on the hundred meter scale) to have a linear depth-length relation. This is best shown by the comparison between the profiles of the upper part of Kuka'iau Cave (i.e. ThatCave) and Pa'auhau Civil Defense Cave (Fig. 9). Also, the general decrease of the passage size with length is a feature more consistent with water flow than of lava flow.

Total stream power (in watts) is calculated from maximal flow, the specific density of water and bed gradient. The total-reach gradient is ca. 100 m/1000 m, i.e., 0.1, or ca. 0.18 if considering only the mauka vadose section of Kuka'iau Cave. This is comparable with other gradients of step-pool streams, such as those given in Wohl and Merrit (2001, Table 2), who list eight rivers with gradients between 0.02 and 0.2 and maximal discharges of between ca. 4 and 700 m³/sec. The overall gradient appears to be the most important factor determining step-pool channels as illustrated by the statistical analysis of Wohl and Merrit (2001) of over 40 river channels. The analysis suggests also that step-pool channels develop where there is a relatively low ratio between driving forces (i.e., stream power) and rock resistance. "The presence of steps and plunge pools, which may result from differential erosion associated with substrate heterogeneity localizes and maximizes erosional force in the plunge pools" (Wohl & Merrit 2001, p. 1211). Since maximal flow of the creek feeding Kuka'iau Cave remains unknown at this stage of the investigation, maximal stream power cannot be determined as yet, but cobble size and inclination of pool-exit chutes should provide clues to estimate this important stream characteristic in further studies.

It is also interesting to consider the temporal aspect of the evolution of the cave. Apparently no model exists as yet which links down-cutting rates of bedrock channels with gradients, water flow and substrate characteristics. Even if such models would exist, it will be difficult to apply them to the ThatCave case, simply because we do not know how active the creek is. We do know - due to a rim of modern flotsam - that the creek periodically floods the cave in present time up to a height of 65 m above the level of the sump. The cave flooded in November of 2000 when the island of Hawai'i experienced an

exceptionally heavy rainy season and in the winter of 2001-2002, as indicated by the tire, which was washed through the cave. However, the cave's formation may well be linked to past climatic conditions, for example, to the time when the ice cap of Mauna Kea melted at the end of the Last Glacial Maximum. Dethier (2001) published a recent overview of river incision rates for the Western United States, using the Lava Creek B Tephra, erupted from the Yellowstone caldera ca. 0.64 Ma ago, as a time Marker Layer. His results show that incision rates ranged from 30 (for very steep terrain in the Rockies) to < 5 cm/ka (along the plains west of the Mississippi/Missouri) since the deposition of the tephra. If such values also apply for ThatCave (average height assumed as 3 m) then the cave could have formed in a period of less than 10 ka to more than 60 ka.

The finding of quartz and illite (a fine-grained mica) in the paleosoil Layer 1 (TC 11 and TC 20) suggests that this soil was exposed to higher dust-fluxes, such as occurring during glacial times. Vitousek *et al.* (1997) describe sites on Mauna Kea with 20 ka old soils and on Kohala with a soil age of 150 ka. Both sites contain dust-derived quartz. Kurtz *et al.* (1999) found a total of 6 g dust per cm² at the 20 ka site and of 14-18 g/cm² in the older sites. We found (sample TC 20) a quartz content of ca. 11% of the total. If we assume a soil density of 1.5 g/cm³ and a layer thickness of ca. 20 cm, one can estimate the quartz content to ca. 3 g/cm². Compared to the Mauna Kea site of Vitousek *et al.* (1997), Layer 1 could have an exposure time of around 10 ka. Total weathering time can be estimated by looking at the feldspar contents. Vitousek *et al.* (1997) show that feldspar is lost between the 20 ka and the 150 ka old sites. Since feldspar is missing in the samples containing quartz (TC 11) and illite (TC 12) (but not in sample TC 21) and in one of our samples from the red Marker Layer (sample TC 15) one must assume that these soils have a weathering age older than 20 ka. Since exposure time and weathering time do not agree, one can tentatively conclude that the weathering of the soils continues even after they have been covered by the next lava flow. This conclusion is also substantiated by the observation that the aa layer above Layer 1 is well weathered (TC 22 and TC 23, compare also Fig. 3), containing large fractions of amorphous matter and only a few percent of feldspar. Apparently the underlying soil served as a water retarder, facilitating the continuation of the weathering reactions. At the same time it is illustrated that water must have collected and flowed above the soil through the interstices of the aa rubble. The presence of magnetite in place of hematite and donathite could suggest that this weathering occurred under reducing conditions, again pointing at weathering within a perched groundwater body.

All these observations allow concluding that the lavas into which the cave system was eroded must be at least predating the last glaciation. They could be as old as 100 ka, but not much older than that, consistent with the published youngest ages of the Hamakua Volcanic Series (see Chapter 2). This limits the age of the cave to a few 10 ka fitting into the considerations derived from the discussion of the erosion rate.

We hope to get a further age constraint of the bedrock of the cave from a charcoal sample recently recovered by Dr. Jack Lockwood in ThisCave from the aa rubble below the diamict.

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