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DEVELOPMENT AND MORPHOLOGY OF KAZUMURA CAVE, HAWAII

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Kazumura Cave is a lava tube located in Puna District on the Island of Hawaii. A brief description and history of the cave is included. Compass and tape surveys in 1994 and 1995 extended the system significantly. This provided an excellent opportunity to study a long master lava tube. Lava deposition and thermal erosion are primary factors affecting the cave morphology. This is demonstrated by passage configuration, multiple levels, invasion of extraneous tubes, and the development of lava falls. Other tube features such as windows, balconies, and rafted breakdown are also discussed. Some features in Kazumura Cave are similar to those associated with carbonate caves and surface water streams.

There is generally a wide range of speculation and controversy regarding lava tube genesis and development. In this paper, we attempt to meld external observation of active tube phenomena and other related research with our underground studies in Kazumura Cave.

Kazumura Cave is located about 20 km south of the city of Hilo in Puna District on the Big Island of Hawaii. In 1966, one of its many entrances was designated as a fallout shelter (Hawaii Grotto News, 1995). It came to the caving community's attention in the early 1970s when Francis Howarth discovered several new troglobitic invertebrate species in this and other nearby caves (Howarth, 1973). An 11.7 km portion was surveyed by a British expedition (Wood, 1981) and then was recognized as one of the longest lava tubes in the world. In 1994 and 1995, teams of the Hawaii Speleological Survey of the National Speleological Society conducted explorations and studies summarized in this paper. To date, the length of the cave is 59.3 km with a vertical extent of 1098 m. Average slope of the cave is 1.9º over the linear length of 32 km. Approximately 17 km of the surveyed passages consist of side branches and passages overlying the main (lowest) level. Also surveyed were additional caves originally part of Kazumura Cave but segmented from it according to criteria described by Crawford (1982). These additional caves total less than one kilometer.

Kazumura Cave carried tholeiitic pahoehoe lava for one of the Ai-laau shield flows originating from Kilauea Volcano approximately 350 to 500 years BP (Holcomb, 1987). The Ai-laau flows spread from 1.5 km long Kilauea Iki Crater, situated just east of Kilauea Caldera at nearly 1200 m elevation (Holcomb, 1987). For interpretational ease, we have divided the cave into five portions (Figure 1, Table 1). The Kazumura Cave flow once drained 39 km toward coastal Kaloli Point, and may have extended the shoreline there, adding an unknown mass below sea level. Analysis of the Ai-laau basalt indicates only a 4° C temperature loss across the 39 km flow (Clague, personal communication, 1995) due to the insulative efficiency of lava tubes.

The character of the cave varies dramatically from a road fill blockage high on the volcano at 1128 m, to the nearly sealed bottom located only 29 m msl. Passage dimensions can be as much as 21 m wide and 18 m high. We grouped 2071 transverse cross-sectional views drawn throughout the cave into ten sizes. These computed to an average cave cross-section of 20.3 m². Using this figure, the volume of accessible cave is nearly 1.2 million cubic meters. Sinuous, smooth, dark gray metallic-looking walls are often gently grooved with horizontal flow ridges. Floors are usually clean pahoehoe, and seldom grade into a clinkery aa surface. In dead-air spots such as side passages, the ceilings and floors can have a very rough, popcorn or frothy appearance, possibly from degassing. The narrow, stacked passages common in the portion closer to the crater gradually change into a single, low, broad-shaped passage further downstream.

The cave is located on the windward, rainy side of the Island, resulting in thriving vegetation that obscures the surface of the flow. At higher elevations, hapuu fern forests predominate, and lower elevation forests contains less hapuu with numerous guava and larger ohia trees. Patches of savanna grasslands are common in lower elevations, and a thick fern understory occurs in the forests. Because of thin soils and the relative new age of Kazumura Cave, we found only two significant silt deposits underground, but entrances have accumulated organic debris of decomposing vegetation. Cave temperature consistently increases from 15° C near Kilauea, to 22° C under the coastal plain.

Prehistoric use of the cave by humans was heavy in the downstream nine kilometers nearest the ocean. Over the years, subsequent vandalism and destructive impacts are extreme on these cultural sites because of overlying subdivisions, roads, and many entrances. We discovered three sewer pipes in the cave, at least three sites of graywater pollution, two significant garbage dumps, and several fills from road construction. Some entrance portions had signs of recreational caving (i.e., trash and shoe fragments) usually ending at drops, or crawlways.

We noted bones from dogs, a bovine, pigs, mongoose, and rats. Numerous invertebrates were seen, commonly on the delicate tree roots hanging from the pervious ceilings. A white,

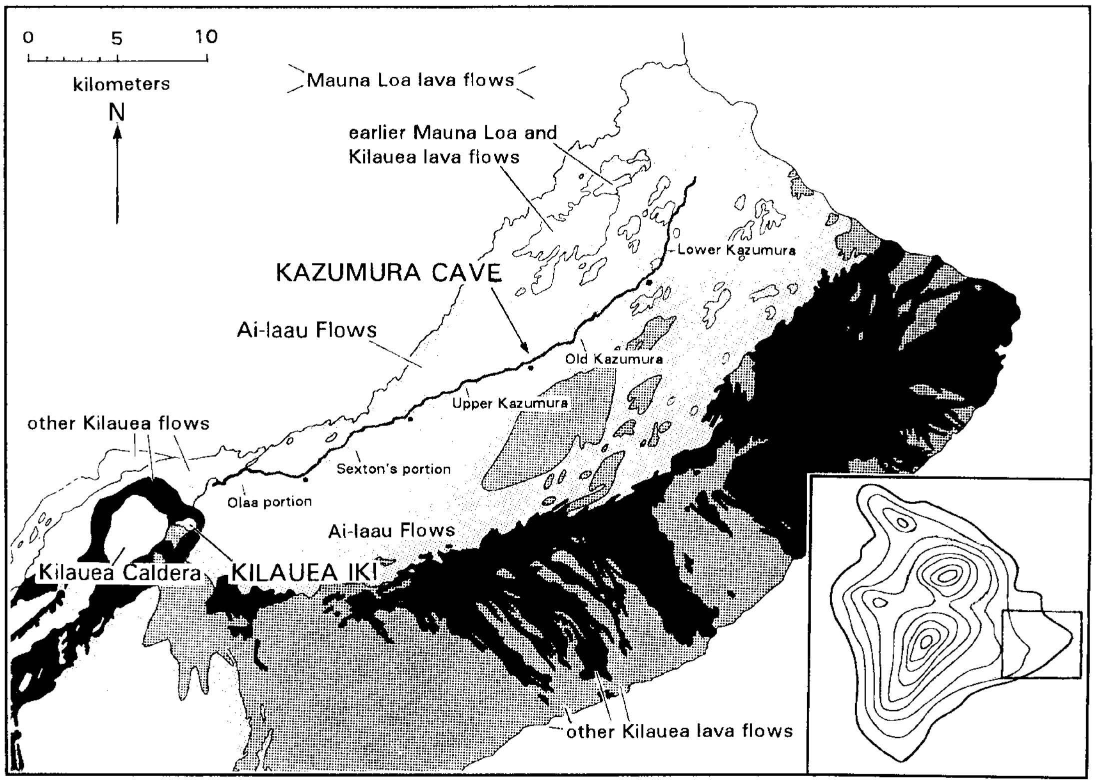

Figure 1. Lava flow boundaries according to Holcomb (1987) showing Kazumura Cave and its five portions.

Table 1. General Statistics of Kazumura Cave. See text for explanation.

Portion of cave	Elevation range, (m)	Surveyed passage (m)	Average slope (deg.)	Est.average passage slope *(deg)	horizontal linear distance (m)	Estimated slopes triggering cascades and falls (degrees)	Estimated erosion depths (m)	Estimated average erosion depths (m)
Olaa	1128 - 899	11751	2.5	2.0	5065	1.4 - 5.9	5.6 - 19.9	12.1
Sexton	899 - 667	14970	2.0	1.6	6626	2.1 - 3.4	3.4 - 17.2	12.1
Upper	667 - 461	10946	1.7	1.4	6963	1.6 - 6.3	4.0 - 11.1	10.5
Old	461 - 186	12556	1.9	1.5	8285	2.0 - 4.5	3.4 - 10.1	9.1
Lower	186 - 29	9014	1.3	1.1	6671	2.3 - 3.6	3.4 - 10.1	7.6

*This is based on surveyed distance through the meanders of the lowest level. The exact slope will be slightly steeper because of survey distance over some obstructions.

red, or gold-colored mold or fungus layer occurs on walls and ceilings. This often grows along paths of the frequent contraction cracks that formed during the cooling of the tube.

METHODS

In order to accurately portray and understand structural complexities of the cave, it was surveyed using fiberglass tapes, hand-held clinometers, and compasses. The detailed sketches included transverse cross-section drawings, with both profile and plan views of all surveyed passages as outlined by Dasher (1994). Aluminum extension ladders were used to reach some passages. Some flagged survey points were left to later correct blunders, tie in new passages and re-locate features in the cave for further study.

We experienced discrepancies of as much as 10° between compass backsights and foresights from magnetism in the basalt. Discrepancies were negligible in other places. Haphazard readings may be from different paleomagnetic qualities of previously deposited strata. The deflections intensify closer to the caldera, causing canting of the rotating portion of the compasses 5 to 10°, even on the surface. Aeromagnetic surveys have shown intensified magnetic anomalies at Kilauea Iki Crater (Flanigan & Long, 1987). Eight "Control Points" were used to re-align the main-line survey to known geographical reference points. Long, whip-like, overlying passages and mazes sometimes had to be corrected to follow the adjustment done by the control points. Using the

SMAPS 5.2 computer program, we compiled and reviewed the data, then made comparisons with other maps of non-Hawaiian lava tubes.

DISCUSSION

PRIMARY AND SECONDARY DEPOSITS

Kazumura Cave contains extensive primary lava deposits of accreted linings and crusts. These and other small formations such as drips were created with the cave itself. Most of the array of lava adornments are described in Larson's *Illustrated Glossary of Lava Tube Features* (1993) and are not described here. However, in several locations, and on two levels within the cave, are remarkable reddish-colored flow features we will call lava blades. Halliday described these forms from Kazumura Cave and from a nearby and detached upper level called Anthurium Sink (Halliday, 1994). Parts of these blades resemble rain-corroded rillenkarren in carbonates (Ford & Williams, 1989). Lava blades consist of regularly spaced parallel grooves and ridges associated with thin blades and fingers leading downstream, sometimes with stringy lava and Peles Hair (Figure 2). They occur not only where wind may have had a role in their formation, but also where the lava stream was restricted and increased in velocity. The trailing fingers, up to 15 cm long, resemble those known to form as a crust-building mechanism in open lava channels (Peterson et al., 1994). They seem to grade into a more common lava tube feature referred to as being "castellated" (Larson, 1993), which we noted on many levees.

Secondary mineral deposits of unknown composition are scattered throughout the cave. These have the appearance of white crusts, needles, and popcorn.

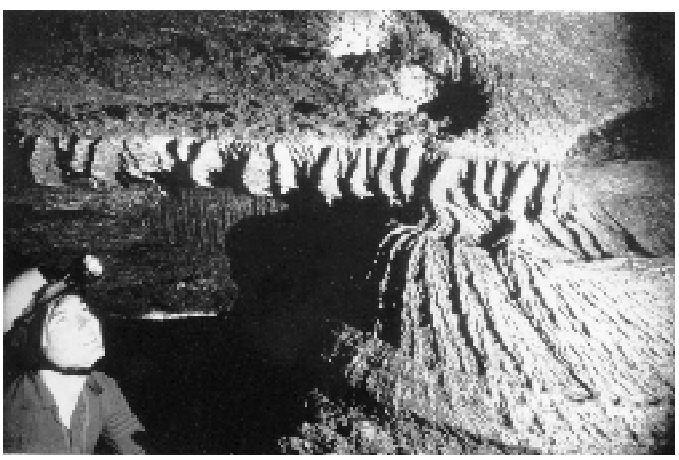

Figure 2. Lava blades in the Upper Kazumura portion at station # B233. The blades are approximately five millimeters thick, and the flow direction was to the right. Photo courtesy of Dave Bunnell.

THERMAL EROSION AS A LAVA TUBE PROCESS

Early in the survey, we were puzzled as to the genesis of the system, other than the basic assumption that liquid lava had drained from an underground conduit, leaving a void. In many places near the ceiling we found elevated benches, alcoves, and side passages. Extensive stacked levels or tiers overlie some lower level passages. Lava tube passages can be filled or altered by accumulation of liquid lava, leaving a rock surface with little or no indication of earlier morphology.

Our primary question was whether the upper levels and side passages we were finding in this cave were formed before or after the lowest level. Three cited theories are: [1] that stacked levels can be formed precisely one atop another from the bottom up by overflows or unassociated flows, with subsequent draining into the deepest level (Greeley, 1971; Arnold, 1986; Rogers, 1990; Waters, Donnelly-Nolan & Rogers, 1990), [2] the simultaneous development of all levels in a thick flow unit (Cruikshank & Wood, 1972), and [3] that thermal downcutting into pre-flow material erodes part of a passage, creating a deep, narrow cross-section (Wood, 1981; Greeley, 1987; Coombs, Hawke & Wilson, 1990; Kempe & Ketz-Kempe, 1992a). Various crustal separations are deposited during this process causing stacked multi-levels (Swanson, 1973). Using computer modeling, Carr (1974) proposed that this thermal erosion occurs when some minerals of the bedrock are melted, and the remainder are swept away and incorporated into the flowing lava. He also concluded that most thermal erosion should occur in turbulent flow conditions. From our observations of incised lava stream slots, canyon-like passage, stacked levels, and abandoned braided mazes, it appears that thermal erosion was a major process of lava tube development in Kazumura Cave.

TUBE DEVELOPMENT

Key components of successful lava tube development are low viscosity, low to moderate flow volume, and uniform flow volume (Peterson et al., 1994). Greeley (1971) concluded that lava channels usually develop along the axis of the most rapid body of a flow. Lava tubes often form in such channels as open lava streams that roof over by various means (Peterson & Swanson, 1974). Greeley (1971) observed roofing over of open braided channels. A braided form is a dividing and rejoining of lava streams as opposed to a simple divergent branching form. Many braids may never have been exposed to the surface as channels. Recent geoelectrical measurements of active "sheet flows" have shown that hidden lava tubes develop within them as the flow front progresses beyond the measurement sites (Hon et al., 1994).

Braided lava tube complexes are most actively flowing near the fore-front delta of the spreading lava flow. Braided lava streams occur because deposition exceeds erosion. We will refer to this process in lava as embryonic braiding.

Whether the embryonic braids began as open channels or closed tubes, once roofing has occurred, they are totally filled with flowing lava. As the flow front extends still further away,

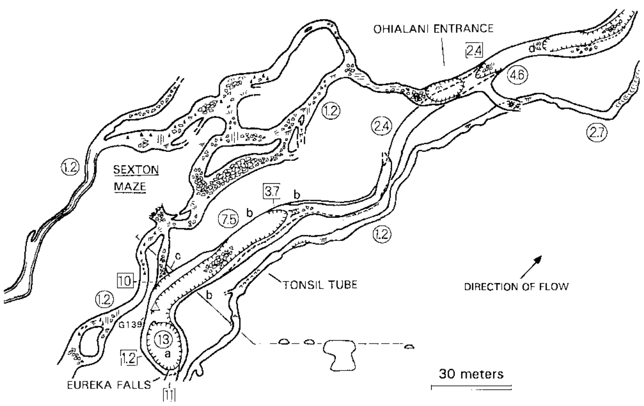

Figure 3. Typical embryonic braiding in the Sexton portion. Note the downcut master tube that finally pirated all of the flow. A simplified profile view is found in Figure 15. (a) plunge pool and secondary widening of the passage caused by the 10.6 m high lava fall, (b) primary widening, (c) a connection at the ceiling between the embryonic braided Sexton Maze and main passage, (d) a lava blade site.

Figure 4. Thermal erosion in the master tube has cut into underlying country rock, sometimes leaving canyon-like passages. View is downstream. The bottom portion of the passage has cut laterally from meander migration. Upper Kazumura portion. Drawing of a photo by K. Allred.

some embryonic braids stagnate, and others become the larger supply arteries that are enlarging deeper and wider due to thermal erosion. The roofs progressively thicken from lava congealing on the conductive ceilings. Arterial cross-section dimensions continue to increase until they carry all the lava volume originally flowing in the braided network. When downcutting in a lava tube exceeds the ceiling accretion in an artery, the stream surface drops away from the ceiling. One or more routes become incised somewhat below the original braided stratum. These passages now become partly filled. Given enough time, an artery becomes a master tube, cutting its way downward into country rock by means of melting and erosion (Figures 3 & 4). A master tube is the main arterial conduit of a large lava flow. In this paper, we define country rock as previously deposited lava, including any newly formed delta lobes overridden by the flow containing the cave.

We assume abandoned braids are often filled or sealed off when they cease to flow. Evidence of this hypothesis is discussed later in this paper. Other dominant braided passages will drain and remain accessible from the master tube. But some can only be found through separate cave entrances on the surface. Cross sections of braided passages are typically low, broad, and lenticular, unless downcut. Access into them from the master tube is often in an upstream direction. Interestingly, these tubes never extend more than about 140 m from either side of the master tube of Kazumura Cave. Considering that most of the overall width of the Ai-laau flows exceeds five kilometers, accessible passage traverses a very narrow strip (Figure 1).

MEANDERS, LOOPS AND MULTI-LEVEL PASSAGES

Typical sinuous curves of the master tube we will call meanders. They are first established by the route of greatest flow volume among embryonic braid tubes through the flow. In time, as an artery becomes downcut and space is created above the flowing lava, heat is lost due to air circulation. A new, lower roof and lateral ledges are likely to be formed, re-insulating the stream from the spacious upper part of the passage, thus conserving more heat (Figure 5). Various examples in the survey demonstrate that a winding route through braids is perpetuated to the downcut lowest level now separated by a crust. A loop (divided passage) which was once part of the braids may continue as a unit during the downcutting. And later one side of the loop may eventually pirate the flow to become the deepest route (Figure 6).

In many places the meanders have migrated significantly (by thermal erosion) from a position directly below the matching embryonic route above. Significant migration suggests long, sustained activity. Four likely reasons for meander changes are: [1] irregularities or weaknesses in underlying rock, [2] large rafted breakdown constrictions causing the passage to be diverted locally, [3] slip banks (Larson, 1993) retained and sometimes built on the inside of curves away from the mean velocity of the lava stream, and [4] cutbanks occurring on the outside of curves where the velocity and turbulence are highest.

Both lateral movement, and general downstream migration of meanders have been detected in many places in the survey by comparing overlying and underlying meanders (Figures 6 & 7). Lateral migration distances were often found to be 1.5 to 2

Figure 5. Multi-level development in the Olaa portion. A third level is 7.5 m above the floor. View is downstream. Drawing of a photo by Carol Veseley.

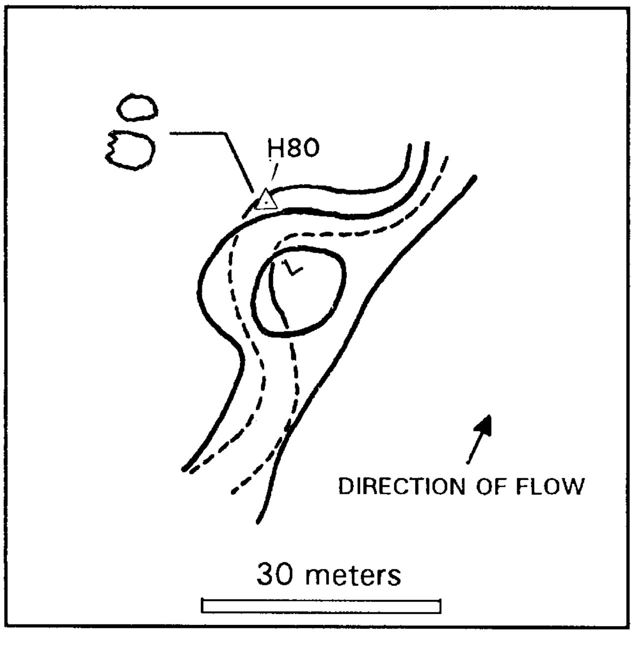

Figure 6. The lower, last active passage (dashed) follows beneath a braided loop in the Sexton portion. During sustained flow, the lava downcut one side of the loop and deposited an insulating crust to separate the cooler upper passages. Note the meander migration.

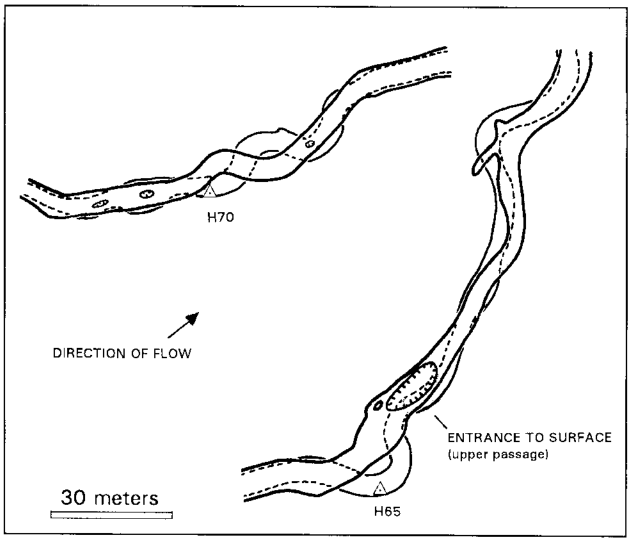

Figure 7. Two plan view examples showing lateral and downstream meander migration in the Sexton portion.

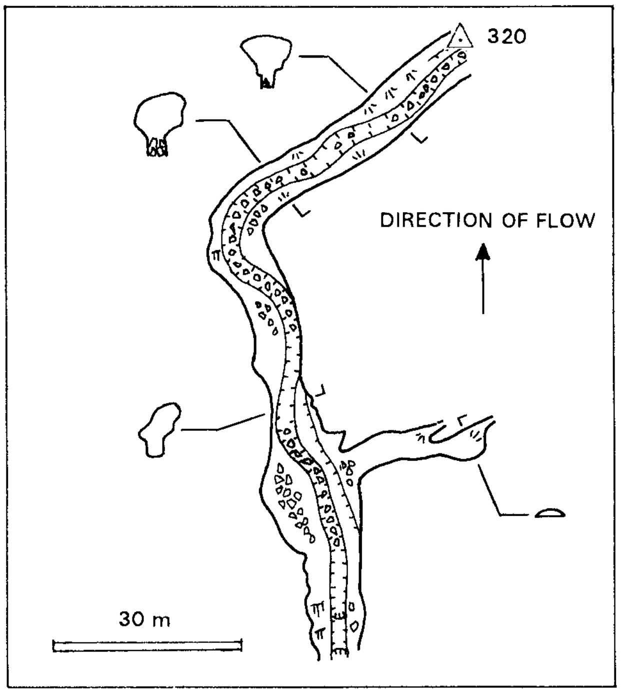

Figure 8. Entrenched meanders; a sinuous canyon developed within the passage in the Old Kazumura portion.

meters. Noticeable downstream movement ranged from 1.2 to 9.1 m. Entrenched meanders within passages are common in downstream portions of the cave (Figure 8.)

We selected 98 stretches of lowest level passage with variable slopes. They were then measured by sinuosity, which is determined by:

PD/LD

Where PD = the measurement along the center axis of a length of cave passage between two survey points, and LD = the linear, horizontal distance between the same two survey points.

Sinuosity ranged from 1.01-1.32, with an average of 1.10 in the upper three portions of cave, and 1.09 in the low two portions. High sinuosity correlates with steeper slopes in 62% of cases, which may be influenced by meander migration on more turbulent slopes. However, more study is needed before this relationship is certain.

EROSION AND STACKED PASSAGE DEVELOPMENT BELOW ENTRANCES

As mentioned above, it was observed that upper levels are remnants of the active tube system before crustal separations occurred. Our observations (Figures 9 & 10) confirm those of Peterson et al. (1994) who witnessed stacked levels forming in active lava tubes from cooling air below entrances. Swanson (1973) observed gradual deepening of the active tubes along with coinciding lowering of the lava stream surface during the 1969-1971 Mauna Ulu eruption, and concluded that the master tubes had eroded as much as 15 m below entrances in 18 months or less. Kauahikaua (personal communication, 1995) successfully measured downcutting of 10 cm/day, which then ceased after a time.

Floor levees are usually found near entrances, and are due to crusting along the lateral sides of the flow from cooling atmosphere. Those that remain today formed during the draining of the last flows through the tubes. When found away from entrances, they indicate areas with air circulation. Levees may grow out to become a tube-in-tube, and some upper levels and embryonic braids contain both. There are a total of 82 entrances, most being accessible through upper levels. We conclude that at least 54 were present prior to the draining of the cave. There was uncertainty about 21 others. One entrance in the Sexton portion and the six most downstream entrances of the cave definitely collapsed after solidification of the flow.

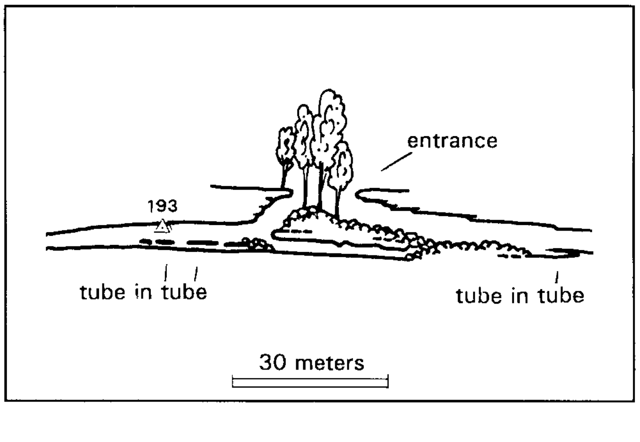

Figure 9. A projected profile view of a typical separation between levels below an entrance of the Old Kazumura portion.

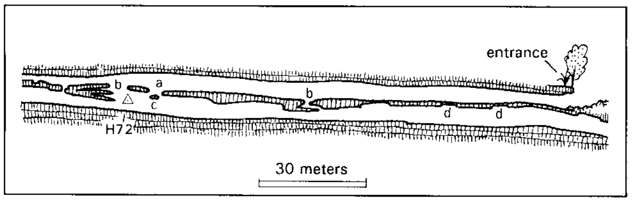

Figure 10. Windows and stacked balconies in a multi-level portion of the cave. Sexton portion. (a) window, (b) stacked and offset balconies, (c) bridge, (d) sealed off windows forming cupolas.

CHARACTERISTICS OF UPPER AND LOWER LEVELS

General appearance of overlying passages is different than that of the lowest and last active level. Upper levels are likely to be wider, and exhibit more uneven floors and walls. Irregularities and alcoves in the walls of upper levels are remnants of the meanders and embryonic braids established in the early delta of the flow. Some of these remnants were not wholly erased as the artery pirated the main flow. All alcoves or embryonic braid passage are now perched above the floor and are commonly found at ceiling level. They are prone to many color shades of flood lava in layers on the walls and floor. In contrast, the lowest or last active level is often smaller in diameter and tends to have developed graceful, smooth, curving surfaces.

Long, lateral ridges, and seams are common in downcut Kazumura Cave passages. We believe that some ridges along walls resembling former stream levels are actually nearly exposed country rock strata under a fairly thin lining as indicated by offset ridges on opposite walls and other irregularities. Locally, flat, unarched ceilings reflect the underside shape of the initial roofing of a channel. Conversely, subsequent flood events promote extensive lining accretion and modification.

Breakdown is more prevalent in overlying passages than in the last active (lowest) level. We attribute the extra breakdown tendency to: (1) wide, less arched ceilings, (2) poor fusing of lining on colder ceilings and (3) cooling and heating cycles which could have affected many of these upper levels during lava tube activity. If a ceiling lining finally weakens and settles during its shrinking process, then is partially heated and expanded again repeatedly, the offset fractures are crushed and then released, akin to cycles of frost wedging (Figure 11). Thermal experiments on basalt (Ryan, 1987) show that after each heating and cooling cycle, irreversible structural strains created a net loss of rock volume. Accumulated thermal cycles of even moderate ranges would therefore shrink and weaken ceilings further. Observations in other Hawaiian tubes during significant earthquakes indicate no further breakdown (Kempe & Ketz-Kempe, 1992b; Werner & Werner, 1992). We believe that, contrary to most local belief, it is rare that any breakdown

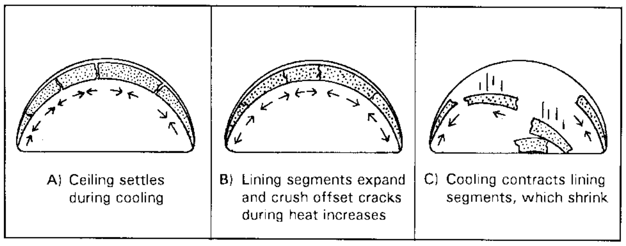

Figure 11. Theoretical promotion of breakdown from thermal fluctuation cycles.

occurs during an earthquake or excavation. The basalt is surprisingly resilient, given its porosity.

WINDOWS AND STACKED BALCONIES

Many lower and upper levels often have an opening, or window, connecting them with a balcony at each end where the floor of the upper level begins. Windows are often much less than six meters long, but can be much longer. Windows generally remain open during active flow. Others could initially be punched through the forming crust from falling breakdown, or would start simply from the early failure of the crust. We often found black or reddish lava that had upwelled from flooding lower levels. Portions later drained back to sometimes leave a collapsed, chaotic, crusty jumble. These upwellings are traced to now-sealed-off or still open windows between levels (Figure 12). In one small window, the black upwelled lava had been turned red where exposed around the lip to the heat from below. The surface of upwelled black lava does not have a skin of glass typical of surface flows where they are exposed to cooler air. This is because the upper levels were still hot during the upwelling. We presume that the air temperature on the lava skin was more than the solidus temperature of lava (980° C) for no glass to have formed (Wright & Okamura, 1977).

Cupolas (shallow domes) are sometimes found in the lower level ceilings below sealed windows (Figures 10 & 12). However, numerous cupolas are lava-lined or post-flow breakdown chambers. No cupolas have been shown, as yet, to be former entrances.

When more than two levels occur, they are often less than 15 m long and stacked one above the other, forming a series of balconies below a window (Figure 10). There may be as many as four different levels, generally with small diameters indicating accretion of linings on higher, cooler walls during flooding. Such multi-level development is predominantly on the upstream side of the initial window. Each stacked balcony in a downward direction is offset further downstream, but only slightly. In other words, the floor ends less than one meter past the break of the ceiling of that same level. Offsetting is more exaggerated in some areas than in others, but the pattern is the same. The questions that arise are “why are some balconies stacked, and why are they typically offset?”

We believe that formation of stacked balconies is related to

Figure 12. A sealed window close to a balcony in the lower Kazumura portion. At least two overflows from the active level deposited rims of reddish lava around the balcony and window before the window became sealed with ropy pahoehoe. A shallow cupola is under the sealed window in the ceiling of the passage below. The overflow feature is 1.8 m wide, and the view is in the downstream direction. Photo courtesy of Dave Bunnell.

gas movement and circulation. Where the main passage is tall enough, or there are upper levels, a strong gas/air circulation was active and driven by the rising heat and flowing lava. We can assume that gas and heat turbulence must have occurred slightly downstream from the window or lowest balcony. Downstream from this zone, a hot, gaseous, breeze flowed upstream. The hot lava surface would not allow a crust to form. A small amount of cool air sinking into the tube from the window promoted crust development below and just upstream where the cool air mixed with the hot upstream gas. These hot gasses are continually released during flowage through the tubes (Cashman, Mangan & Newman, 1994). Windows into upper levels and to entrances act as important circulation and gas release ports. Entrances can also serve for breakout flows (Peterson et al., 1994) building up the ground surface.

Stacked balconies locate in the tube where temperatures cannot be cooled much by entrances. Just enough heat should exist to impede downstream crustal development, yet enough heat loss upstream from the windows forms another upstream tier. Where cooling influence is greater, the offset distance tends to be increased and levels may also form downstream from windows. Subsequent flood lava and gas turbulence may then modify the newly formed balcony lip, and the new level will usually plug at the upstream end because of floating crusts.

RAFTED BREAKDOWN

When fragments of breakdown end up in lava, they can become coated or partially melted into a more rounded form. Rafted breakdown (of either rocks or boulders) is most often found cemented to surfaces of upper levels, and can be lodged in constrictions to form full, or partial blockages. We reasoned that if vesicular breakdown were less dense than the flowing lava, the breakdown would tend to float into upper levels during flooding. To test this theory, we measured bulk rock specific gravities of 12 miscellaneous breakdown fragments (Table 2). The most common samples were vesicular ceiling lining (between about 1.5 g/cm³ and 2.0 g/cm³) built downward from buoyant lava or floating crusts. Swanson (1973) demonstrated increased specific gravities and decreased porosity as tube-fed lava flowed further from the 1969-1971 Mauna Ulu Kilauea eruption (Table 2). In Kazumura Cave the densest lining of an area probably reflects the approximate specific gravity of the submerged lava that flowed through that area. Three small rafted rocks adhering to an upper level wall were also sampled. One rafted rock contained an angular, vesicular core with two layers of more dense lining. The other smaller rafted rocks had rounded cores which were slightly more dense than their thin, singular lining. We conclude that the deeper portions of the lava flow upstream from #B204 had specific gravities higher than the core of the most dense rafted rock (2.11 g/cm³) which had to be buoyant enough to stick up on the wall. This agrees nicely with the 2.33 g/cm³ and 2.36 g/cm³ lining measurements just upstream. Most rafted breakdown that remains in the lowest active passage is probably flushed through the system or melted. "Lava Ball Hall" (near station

Table 2. Bulk Rock Specific Gravity Measurements.

Sample	Description and location of sample	Specific Gravity	Vesicularity (percent)*	Distance from vent (km)
1	Lining, Upper Kazumura Portion, #B204-B247	1.51	50	13.5-14.5
2	Lining, Upper Kazumura Portion, #B204-B247	1.53	49	13.5-14.5
3	Lining, Upper Kazumura Portion, #B204-B247	1.58	47	13.5-14.5
4	Lining, Upper Kazumura Portion, #B204-B247	1.61	46	13.5-14.5
5	Lining, Upper Kazumura Portion, #B204-B247	2.36	21	13.5-14.5
6	Lining, Upper Kazumura Portion, #B204-B247	1.59	47	13.5-14.5
7	Lining, Upper Kazumura Portion, #B204-B247	2.33	22	13.5-14.5
8	Lining, Upper Kazumura Portion, #B204-B247	1.94	35	13.5-14.5
9	Tiny rafted rock, Upper Kazumura, upper level at station #B204A.	1.95	35	14.5
9a	Core of #9.	2.08	31	14.5
10	Small rafted rock, 13cm long, #B204A.	2.03	32	14.5
10a	Core of #10.	2.11	30	14.5
11	Small rafted rock, 19cm long, #B204A.	1.77	41	14.5
11a	Angular core of #11, some impregnation of lining into core.	1.85	38	14.5
11b	Linings of #11.	2.51	16	14.5
12	Shark tooth stalactite (lining) Old Kazumura Portion, near #180.	2.7	10	25
13	Lining. Lower Kazumura Section near end of cave.	2.17	28	35

Specific Gravities of tube-fed molten lava samples (after Swanson, 1973).

1	Mauna Ulu, dipped from summit fissure.	<1 to 1.49	50 - 70	0
2	Mauna Ulu, collected through window in tube.	1.73	42	4.5
3	Mauna Ulu, Surface ooze fed by tube.	1.84	38	10
4	Mauna Ulu, Collected where lava emerges from tube at coastline.	2.48	18	12

*Based on 3.0 g/cm³ of basalt. Possible segregations (Wright and Okamura 1977, pp. 42,43) in linings are not considered, which may alter the density and vesicularity ratios.

#H100) is an upper level entirely coated on ceiling and walls with rafted breakdown. An extraordinary, well-sorted, slip bank of small thinly glazed rocks is found in the lowest level, at station #J34 in the Olaa portion.

BLACK LAVA INTRUSIONS INTO KAZUMURA CAVE

Black, glassy-skinned lava flows intruded through several entrances. Two remained fluid long enough to flow as far as 480 m into the cave and plug it. These were excavated enough to squeeze past them. Contraction cracks in the Kazumura Cave walls did not match those in the black intrusions. The glassy skin and unmatching cracks lead us to conclude that these flows entered Kazumura Cave after it had cooled.

EXPOSED COUNTRY ROCK AND INVADED TUBES

Uncharacteristic of the remainder of the system are a number of massive wall lining collapses in Kazumura Cave about two kilometers northeast from Kilauea Iki (Figure 1). These may have resulted from sporadic draining and partial cooling during pauses in the flow output. Several display exposed inner veneers of lining, and extensive expanses of country rock that the cave had eroded through. Thin pahoehoe beds and more massive aa flows are clearly exposed. This country rock is commonly baked to a reddish color similar to pyroclastic flows exposed behind walls of some lava tubes of Mt. St. Helens, Washington (Greeley & Hyde, 1972).

We found some sites of black, glassy-skin lava from the Kazumura Cave flow itself. Two meters above the base of a four meter high lava fall called “Crumbling Edge Climb” (at station #S7), part of the wall has fallen away. This exposed an

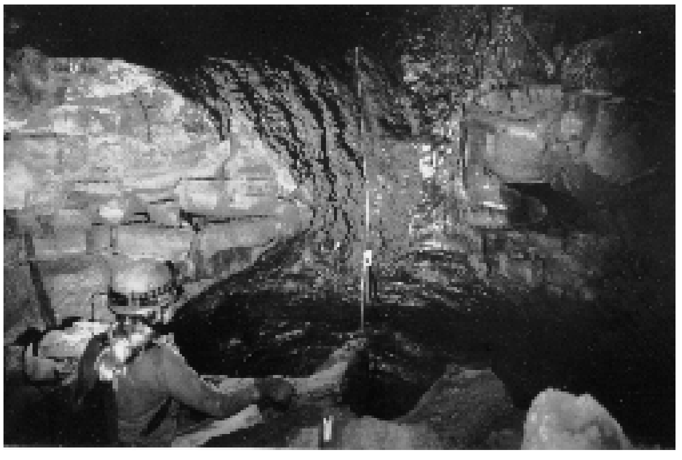

Figure 13. The plunge pool chamber below the four meter high Crumbling Edge Climb (falls) in the Olaa portion. The wall lining collapsed at some time during the activity of Kazumura Cave, allowing Kazumura Cave lava to flow into an unrelated lava tube in the country rock. Subsequent collapse after the cessation of flow again exposed the country rock and an entry into the invaded tube on the far right, center. The ascending device on the 11 mm diameter rope is 18 cm long. Photo by K. Allred.

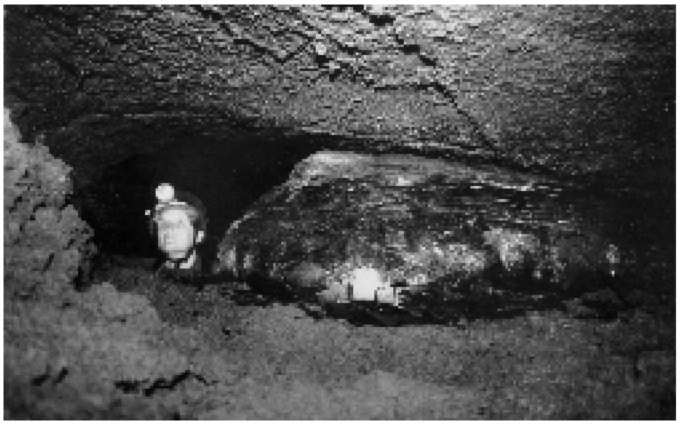

Figure 14. View into Kazumura Cave from the unrelated lava tube shown in Figure 13. The quickly cooled intrusive black Kazumura Cave lava has formed a glassy skin. Photo by K. Allred.

entry hole to a small unrelated embryonic braid-type lava tube in the country rock (Figure 13). A black, glassy toe of lava can be seen intruded from Kazumura Cave into the older tube (Figure 14). Other smaller braid-type passages in the exposed country rock also contain toes of black, glassy-skin Kazumura Cave lava. As with the unrelated black intrusions into Kazumura Cave described earlier, whenever the hot Kazumura Cave flow intruded into cooler voids of the country rock, the lava could not flow far before solidifying. It would appear that unless invaded lava tubes are already hot, it is likely that an unrelated lava flow will quickly plug them. Greeley (1971) witnessed such an event, and later stated that with some exceptions, reused tubes usually become plugged (1987). Peterson and Swanson (1974) describe a lava lake surging into a nine month old (still somewhat hot) inactive tube, and draining out one or two kilometers away.

Some of the most fascinating features we found in Kazumura Cave were three large, oval-shaped bulges protruding from the otherwise uniform walls of the country rock. These were at stations #J25, #J28, and one in an upper level at #OC21. A portion of each had fallen away, exposing unrelated, embryonic braid-type passages. In each instance, these air-filled tubes had apparently cooled the country rock immediately surrounding them, promoting a resistive rind 10 cm to one meter thick. It is only when the weakened rind partially breaks away at some time during the activity that these tubes can then be invaded, and only for a short distance. Another, similar but unfractured bulge was discovered, and likely also contains an extraneous tube. At survey #B213 in the Upper Kazumura portion, the downcutting passage was diverted three meters laterally by an inferred extraneous tube in the floor.

Also close to Kilauea Iki, one massive wall collapse occurred at a balcony at station #R17. This exposed country rock, the original downcut canyon lining, and the cross-section of the balcony between the two levels. At a bulge in the canyon wall, some thin beds of pahoehoe country rock had

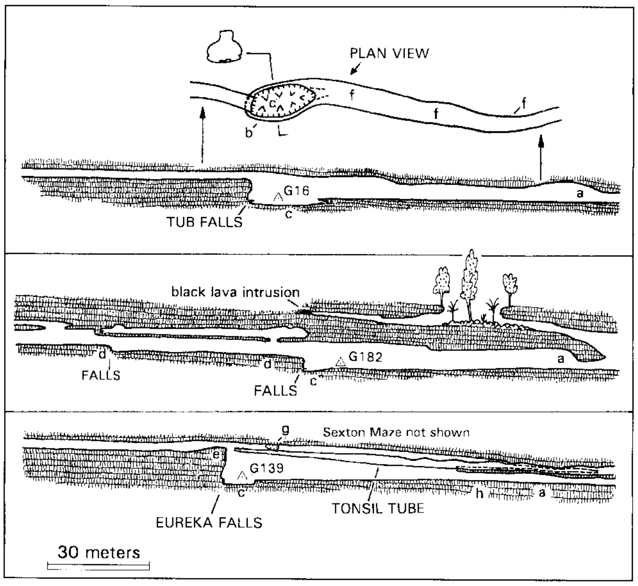

Figure 15. Some projected profile views of typical lava falls. Sexton portion. (a) beginning area of backcutting, (b) secondary passage width enlargement, (c) plunge pool, (d) the development of a stepped floor with any significant slopes taken up by falls, (e) lip build-up, (f) primary widening, (g) a connection between the main passage and the embryonic Sexton maze, (h) a stacked passage below a fall.

been plastically deformed and pressed down into a clinkery layer as the downcutting continued past. We found no old soil, ash, or charcoal horizons in any country rock exposures.

LAVA FALLS

Some of the most spectacular features in Kazumura Cave are the lava falls (Figure 15). These falls are sometimes located just upstream from entrances in actively flowing tubes (Peterson et al, 1994; Nova, 1995). Clague (personal communication, 1995) observed eddying on the surface of one plunge pool causing lava to run in an upstream direction. Volcanologists who have observed active falls inferred that they formed from the eroding floor of one active lava tube collapsing into another older, unassociated tube (Cruikshank & Wood, 1972; Peterson & Swanson, 1974).

We observed that Kazumura Cave lava falls always contain a high, wide chamber at the bottom, and sometimes display large drips and stalagmites. The detailed survey of Kazumura Cave reveals clues of the genesis and development of these falls. Passages near the falls often indicate that in early stages of the flow, the region just downstream from the present fall was slightly steeper than upstream from the lip. The abnormally high ceiling at the falls gradually becomes lower downstream. This ceiling generally reflects the original early tube ceiling, at least for some distance, and indicates that the fall has backcut into the slope. Estimated backcutting (headward thermal erosion) distance shows that falls formed in slopes from 1.6 to 6.2° (Table 1). On these moderate to steeper slopes, flow would tend to be more turbulent than laminar.

A second manifestation of backcutting migration is passage widening due to hot turbulence at the bottom of the falls. In many instances the passage width enlargement ended precisely where the downstream ceiling height became more level. As a steep section continues upstream, the lava fall will increase in height while aggressively backcutting. This incredible force causes deeper plunge pools and wider passage. With the cessation of upstream migration, a secondary, even wider area is gradually melted around the lava plunge pool. Thus, we conclude that all the lava falls we observed, developed in the lowest level of the tube from thermal erosion due to lava turbulence.

We found no evidence of falls permanently forming due to clogging in a lower level, overflowing into an upper level and then pouring down through a window. However, we did find the remains of temporary minor overflow drainage through at least one window down into an intermediate level.

In some instances, falls apparently migrate with cascades. The cascade is always above the fall. When back-cutting reaches more level passage, the fall may finally catch up with and incorporate the cascade.

In several areas, lava falls formed even within sections of only moderate inclination (1.6 to 2°). In these less steep, uniformly inclined passages, the survey shows sections as being

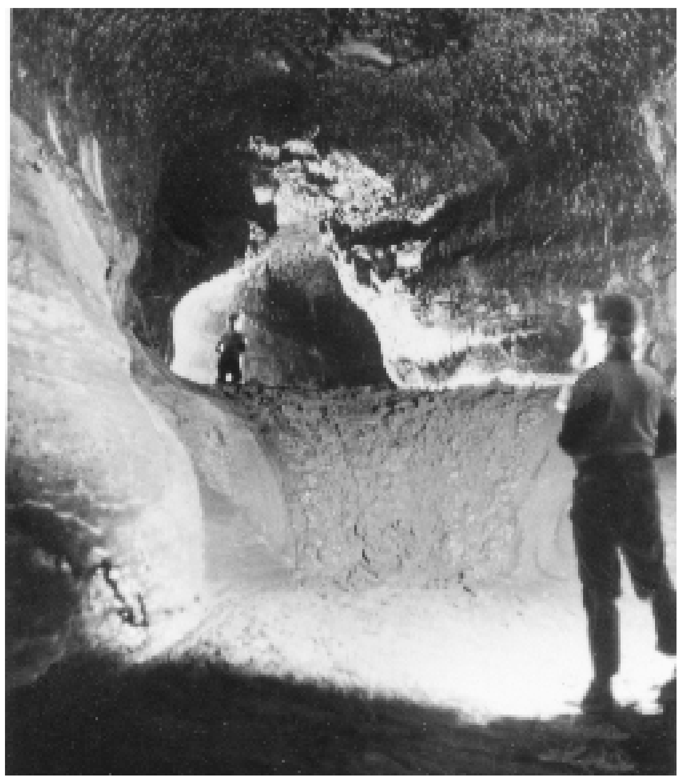

Figure 16. A lava cascade in the Old Kazumura portion. Photo by K. Allred.

Figure 17. Level passages are small diameter just upstream from mature lava falls as a result of lining accretion in laminar flow conditions, along with cooling influence from downstream. Station #R54, Olaa portion, looking downstream. The white colors are unknown secondary deposits and organic slime. Photo courtesy of Dave Bunnell.

steeper during early downcutting, which would set the stage for rapids, cascades (Figure 16), and, finally, a fall. Large lava falls have very level floors downstream. This represents the former slope now taken up by the falls' migration. Some of them also have level floors upstream. In a moderate to steep slope, given enough time with hot enough lava, the entire active level will eventually take on a stepped structure with any significantly inclined areas incorporated into lava falls (Figure 15d).

When the falls are undercut, the floor tends to be level upstream from the lip. This would indicate that upon reaching more level terrain, backcutting at the lip is exceeded by undercutting at the plunge pool. A closer look of level areas above falls revealed striking evidence that backcutting may cease altogether. These upstream passages always have a relatively small diameter (Figure 17), showing that the deeper, slower moving lava does not erode and might even deposit a lining. Air currents at the ceiling from a downstream entrance, upper level, or the large chamber below the lava falls appear to retard backcutting and promote lip buildup (Figure 15e). In fact, the survey indicates that on some of the falls with the longer level upstream areas, a lip buildup of 1.5 m actually lengthens the level area. As this buildup continues, the lava stream deepens, slows, and turbulence lessens even more until an equilibrium is reached. It is not until the slow-moving stream leaves the abrupt lip that turbulence increases.

An inventory of 41 of the highest lava rapids, cascades, and falls in the cave reveals interesting correlations between level upstream sections as opposed to inclined ones (Table 3). Larger falls will have the turbulence necessary to develop all the attributes of mature lava falls. These attributes are: [1] downcutting and backcutting a deeper passage into a slope, [2] creating a primary widening, [3] reaching a level area upstream with likely lip buildup, and finally, [4] a secondary widening around a deeper plunge pool, usually causing undercutting.

Some of the lava falls appear to have not backcut at first glance because of low ceilings, narrow passage or upper levels beginning closely downstream from the falls. However, because of the decreased gradient, some downstream passages have been modified or reduced in diameter from accretion. These falls then also follow the pattern of development.

Further up in the Olaa portion, some mature falls have narrow trenches incised through the falls' lips. This may have been caused by deposition and passage modification just downstream of the falls, altering air circulation and heat distribution at the lip.

Glazed wall linings are as little as 0.5 centimeter thick around aggressively eroded plunge pool chambers of falls near Kilauea Iki. The glaze has the appearance of melted country rock rather than congealed lining from the plunge pool (Figure 18). Basalt had been preferentially melted around the bedding.

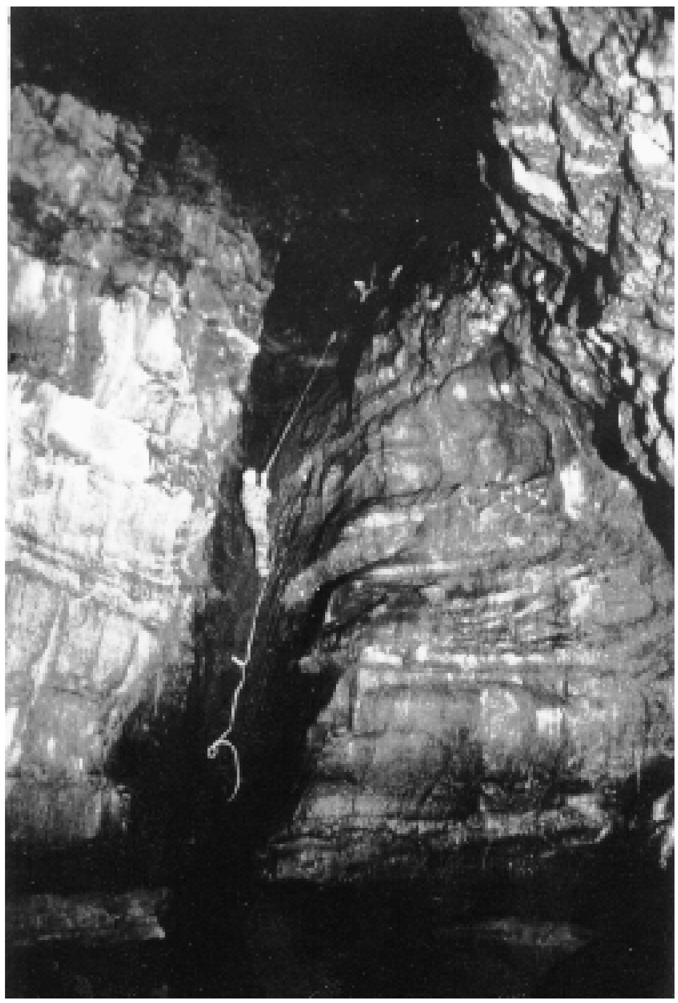

Figure 18. Skylight Falls is 12.1 m high, and located in the Olaa Portion. A very thin lining covers bedding of the country rock around the plunge pool chamber. Photo courtesy of Dave Bunnell.

Table 3. Kazumura Lava Falls. Mature lava falls are identified from level floors upstream of lips and then may develop undercutting and secondary widening. Many smaller lava rapids, cascades, and falls are not included in this chart. Multiple levels and other accretion may form downstream after the migration of a falls. Thus, actual migration distance may vary from measured enlargement distances. Entrances located within 117 m are noted with ^.

Cave portion	Survey number	High ceiling distance (m)	Primary widening (m)	Secondary widening (m)	Feature Height (m)	Undercut	Level upstream
Olaa	T11	<85	85	21.3	High Hopes Falls 7	yes	yes
Olaa	S7	97.5	64	30.4	Crumbling Edge (Falls) 3.9	yes	yes
Olaa	R1	60.9>	60.9	16.7	Dribletspire Falls 7.9	yes	yes
Olaa	R29	<96	47.2	13.7	falls 3	yes	yes
Olaa	R50	73.1	76.2	22.8	falls 2.4		yes
Olaa	QA6	24.3>^	41.1	18.2	falls 11.2	yes	yes
Olaa	P46	60.9	62.5		falls 3		yes
Olaa	P37	48.7^	21.3	18.2	Skylight Falls 12.1		yes
Olaa	P23	24.3	22.8		cascade 3		
Olaa	P3	27.4^	24.3	18.2	cascade 4.5, falls 3	yes	yes
Olaa	O47	53.3^	42.6	19.8	Wild Pig Drop (falls) 13.7	yes	yes
Olaa	O35	32.9^	25.9	12.1	Natural Bridge Cascade 4		yes
Olaa	O10	57.9^	38.1		Pele's Cascade 4.5		
Olaa	J67	36.5	47.2		rapids 4		
Olaa	J51	51.8^	48.7	15.2	Handline Falls 4.5	yes	yes
Olaa	J46	47.2	27.4		falls 1.5		
Olaa	J37	88.4	48.7	12.1	Red Falls 13.7	yes	yes
Sexton	H32	48.7^	33.5>	6.0	falls 3		yes
Sexton	H17	51.8 slight	60.9	9.1	falls 4.8	yes	yes
Sexton	G205	67	73.1	22.8	falls 3.3	slight	yes
Sexton	G189	35^	25.9		falls 6		
Sexton	G182	30.4	18.2		falls 2.4		
Sexton	G142	15.2	22.8		Mongoose Falls 3		yes
Sexton	G139	92.9>	94.5	15.2	Eureka Falls 10.6	yes	yes
Sexton	G120	43.9^	47.2	12.1	Red Column Falls 9.1	yes	yes
Sexton	G79	43.2	25.9 slight	12.1	S Curve Falls 3	yes	yes
Sexton	G25	62.5	53.3>	15.2	cascades 1.2, 1.2, .9		
Sexton	G16	42.6	70.7	18.2	Tub Falls 6	yes	yes
Upper	B249	89^	87.1		falls 2.4		
Upper	B220	88.4	77.7		falls 3.6		
Upper	B196	30.4	33.5		Sickle Falls 6	slight	nearly
Upper	B194	36.5	48.7 slight		falls 1.8		
Upper	B184	30.4	99 slight		falls 9.1		
Upper	B154	22.8	36.5	22.8	Sucker Falls 6	yes	yes
Upper	B14	30.4	insignificant		falls 3		
Upper	B4	9.1^	insignificant		cascade 1.8, falls 1.2		
Old	36	107.6	83.8		cascade 1.2, falls 2.1		
Old	54	44.2	45.7		cascade 2.4		
Old	121	33.6	33.5		falls 2.4		
Old	244	22.8^	129.5		falls 3.6		
Lower	DB25	45.7	45.7		cascade .9, falls 1.5		

This permitted dip measurements, which were between 5 - 6° at two lava falls, confirming that the pre-flow slope was relatively steep in these areas. Scattered angular scars still visible under the thin lava glaze of these bedded walls are evidence that fragments occasionally fell away during the turbulence.

RAMIFICATIONS OF DOWNCUTTING AND GAS CIRCULATION

Lava tubes are known to play a vital role in the building of nearly level shield volcanoes (Peterson et al., 1994). It should be noted that upper levels and tall passages with atmospheric circulation disperse heat. This lowers the insulating efficiency of the system somewhat. There cannot be any other recourse

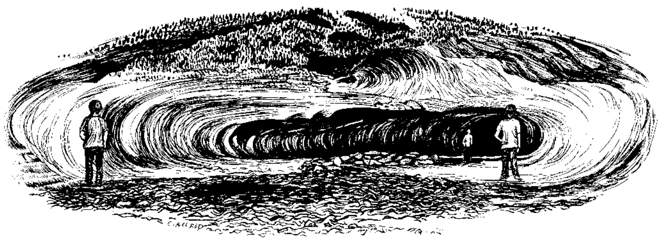

Figure 19. Low, wide passages are often found where the gradient is nearly level. Exaggerated widths as this are most common under the coastal plain in the Lower Kazumura portion. View is upstream. Drawing of a photo by K. Allred.

on steeper slopes near the eruption site with so hot a lava. It does cut down, create multiple levels, and lose some heat through gas circulation in addition to conductivity of floors and walls. Downstream on the coastal plain, the way becomes less steep and lava is less erosive. The tube has fewer upper levels and becomes more heat conservative as the flow reaches further from the eruption site (Table 1).

High, voluminous passages act as limited storage buffers to help regulate flow and keep flood lava within the tube system. Temporary storage of flow fluctuations helps regulate tube forming conditions. This would increase the proportion of deposition on lower slopes of a shield volcano. On a larger scale, Peterson et al. (1994) stressed the role of the Alae Pit Crater lake in modulating erratic eruptive output of the Mauna Ulu eruption between 1969 and 1973.

Low, wide passages occur commonly where the slope is negligible to 0.5°. This extra widening may have begun very early in the flow where the stream tended to spread out. Cruikshank and Wood (1971) stated that on very gradual slopes, active open channels are wide and the walls are preferentially eroded, especially on the outside of bends. Extensive portions of cave with such passages are under the coastal plain, and, to a lesser degree, under a bench area at Volcano Village close to Kilauea Iki. Cooler lava temperatures and a more limited flow time at the coastal plain could have been contributing factors to an exaggerated passage width of up to seven times the height (Figure 19).

The survey hints that the accessible cave passages may be part of a divergent branching system on a grand scale. But much more exploration is needed in nearby caves to determine their true relationship. Observations and detailed mapping of such a long, well-preserved lava tube affords an unsurpassed model to better understand other systems. Although morphologies differ in lava tubes elsewhere in the world; all master tubes we have examined seem to exhibit thermal erosive characteristics comparable to Kazumura Cave.

LAVA AND WATER ANALOGIES

Although the physical properties of lava and water are very different, they are both minerals in a fluid state. Their dynamics are often similarly manifested. Associating some lava features with more familiar processes can help us understand their origin.

For instance, a braided lava stream complex resembles braided water rivers, because in both processes deposition exceeds erosion. The function of lava tubes completely filled with lava can be compared to that of water-filled phreatic carbonate cave passages. Preferential enlargement of a route through a carbonate cave network (Bögli, 1980) parallels the way lava behaves in a braided network. As with vadose stream-cutting in carbonate caves (Bögli, 1980), canyon-like passages can also form in lava tubes. Lava stream meander changes are much like those in water rivers. Low density breakdown can drift in a lava stream like the woody debris or ice floating down a water river. Lava tubes and carbonate caves both contain enlarged chambers and plunge pools below falls.

SUMMARY

We conclude that much of Kazumura Cave began as braided networks, which evolved into a master tube. Thermal erosion increased with turbulence caused by steeper slopes. Reinsulation of the lava stream created multi-level development in spacious, downcut passages, especially below entrances. Although much of the initial passage morphology has been obscured by lava accretion, enough has remained to detect genetic relationships.

Sufficient slope, heat, flow consistency, and time all contributed to deeply eroded passages, lava falls, and the development of a stair-step descent of this master tube. Downcut passages provided limited storage of flood lavas during temporary surges or blockages. This appears useful in regulating the volume and contributing to the nearly flat profile of this shield volcano.

Some lava tube processes resemble those of surface water streams such as braiding and meander migration. Preferential enlargement of liquid-filled embryonic passages, “vadose” modification, and fall development are similar to those found in carbonate caves.

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