JOURNAL OF CAVE AND KARST STUDIES

August 1997
Volume 59 Number 2
ISSN 1090-6924

The
National
Speleological
Society
Bulletin

THIS ISSUE:

Journal of Cave and Karst Studies

Volume 59 Number 2 August 1997

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Articles

The *Journal of Cave and Karst Studies*, formerly *The NSS Bulletin*, (ISSN 1090-6924) is published three times a year by the National Speleological Society, 2813 Cave Avenue, Huntsville, Alabama 35810-4431; (205) 852-1300; FAX (205) 851-9241, e-mail: nss@caves.org; World Wide Web: http://www.caves.org/~nss/. The annual subscription fee, worldwide, by surface mail, is $18 US. Airmail delivery outside the United States of both the *NSS News* and the *Journal of Cave and Karst Studies* is available for an additional fee of $40 (total $55); The *Journal of Cave and Karst Studies* is not available alone by airmail. POSTMASTER: send address changes to the *Journal of Cave and Karst Studies*, 2813 Cave Avenue, Huntsville, Alabama 35810-4431.

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Cover: Grotta di Serra del Gufo. See Galdenzi, page 81.

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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,

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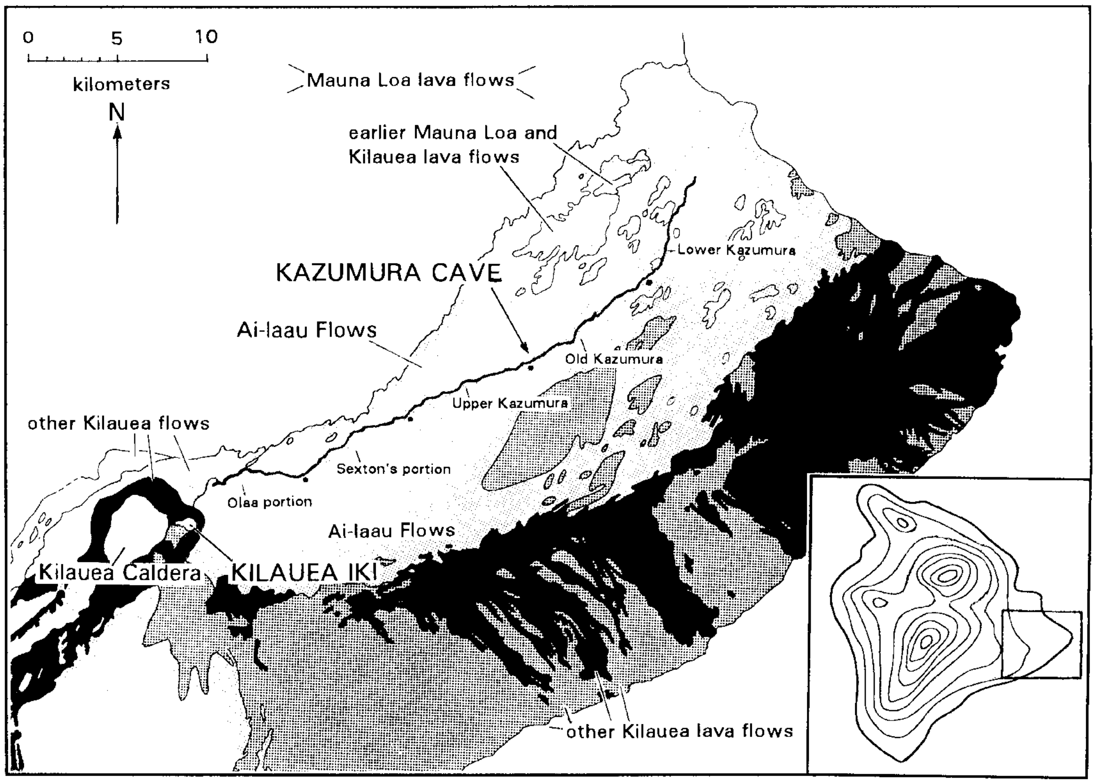

Figure 1. Lava flow boundaries according to Holcomb (1987) showing Kazumura Cave and its five portions.

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.

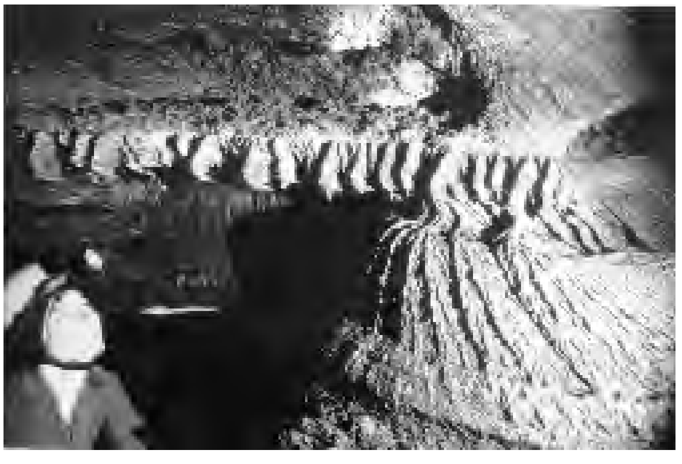

Figure 2. Lava blades in the Upper Kazumura portion at station # B233. The blades are approximately five millimeters thick, and the flow direction was to the right. Photo courtesy of Dave Bunnell.

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,

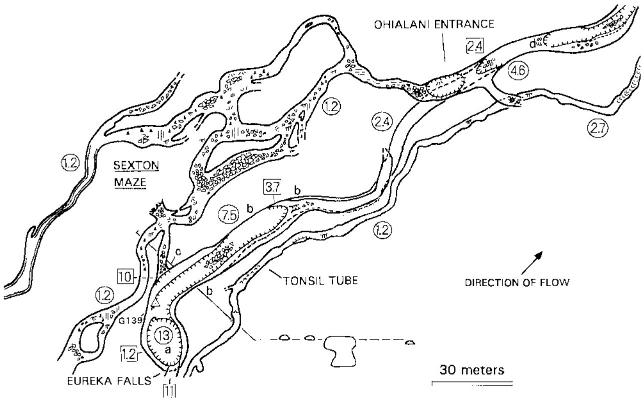

Figure 3. Typical embryonic braiding in the Sexton portion. Note the downcut master tube that finally pirated all of the flow. A simplified profile view is found in Figure 15. (a) plunge pool and secondary widening of the passage caused by the 10.6 m high lava fall, (b) primary widening, (c) a connection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

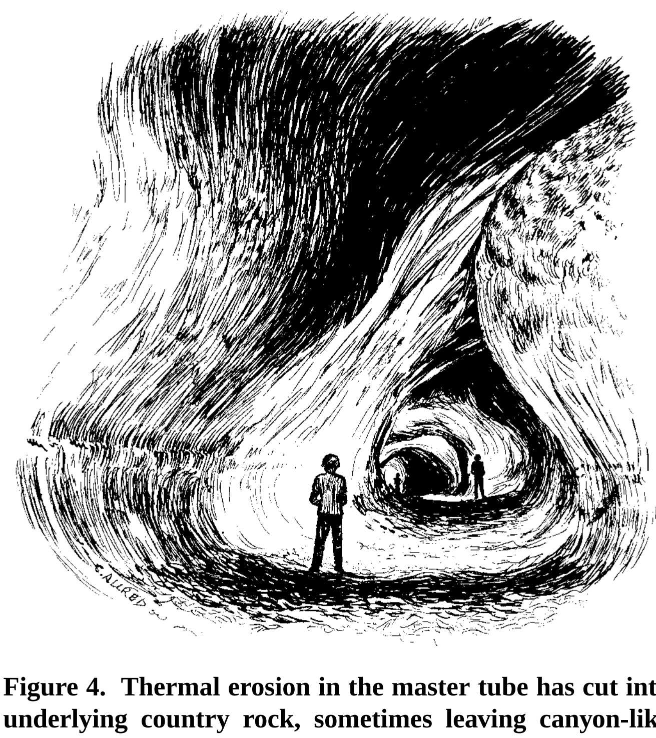

Figure 4. Thermal erosion in the master tube has cut into underlying country rock, sometimes leaving canyon-like passages. View is downstream. The bottom portion of the passage has cut laterally from meander migration. Upper Kazumura portion. Drawing of a photo by K. Allred.

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, reinsulating 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.

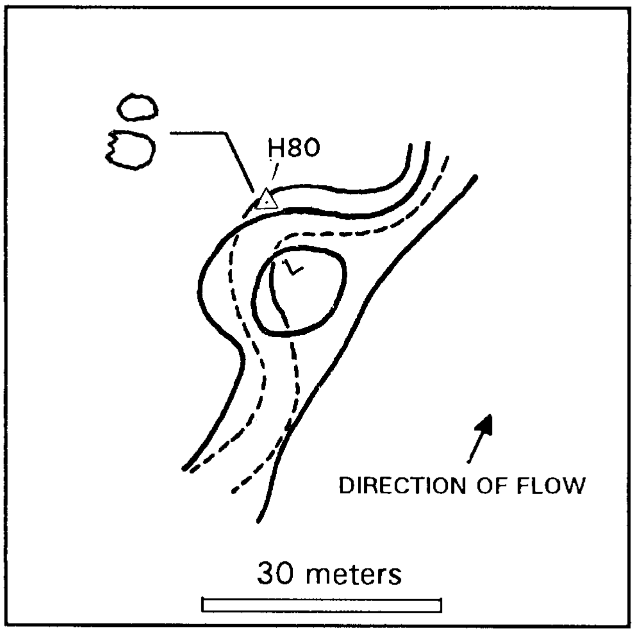

Figure 6. The lower, last active passage (dashed) follows beneath a braided loop in the Sexton portion. During sustained flow, the lava downcut one side of the loop and deposited an insulating crust to separate the cooler upper passages. Note the meander migration.

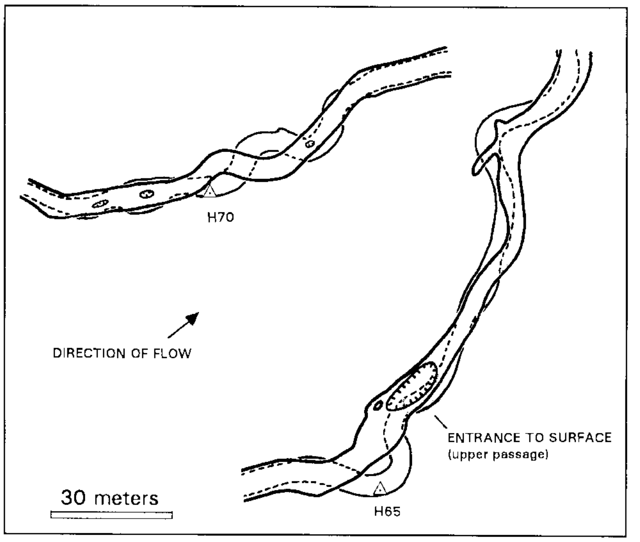

Figure 7. Two plan view examples showing lateral and downstream meander migration in the Sexton portion.

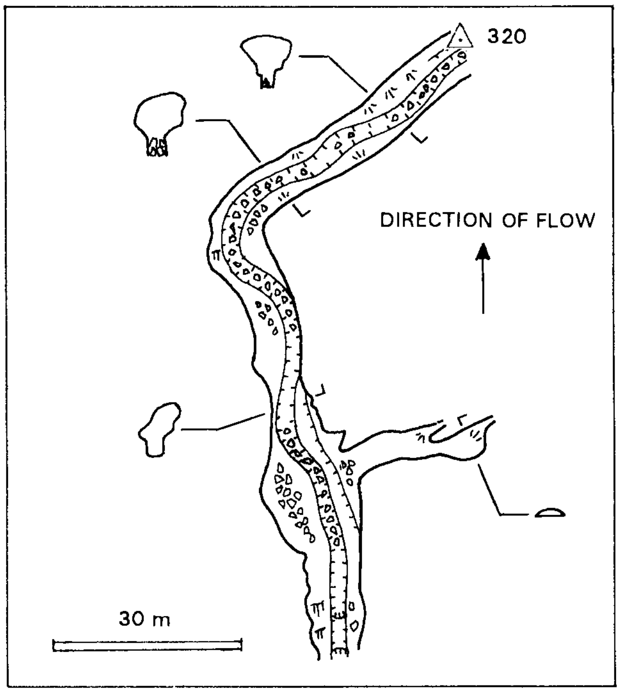

Figure 8. Entrenched meanders; a sinuous canyon developed within the passage in the Old Kazumura portion.

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.

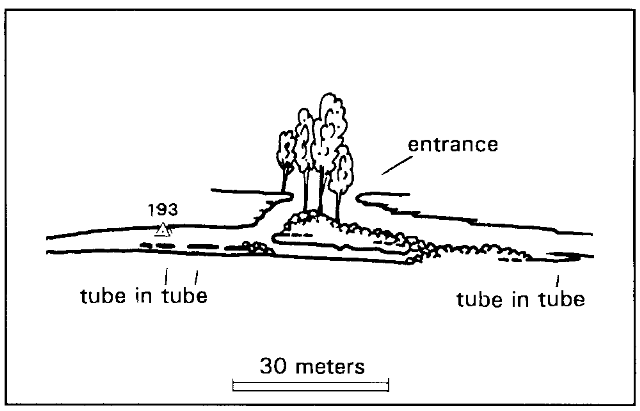

Figure 9. A projected profile view of a typical separation between levels below an entrance of the Old Kazumura portion.

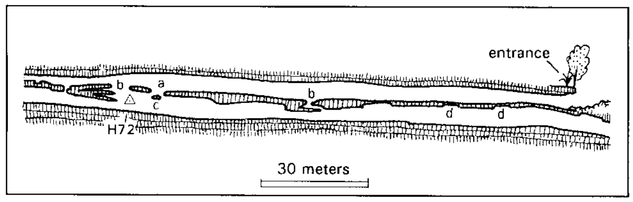

Figure 10. Windows and stacked balconies in a multi-level portion of the cave. Sexton portion. (a) window, (b) stacked and offset balconies, (c) bridge, (d) sealed off windows forming cupolas.

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

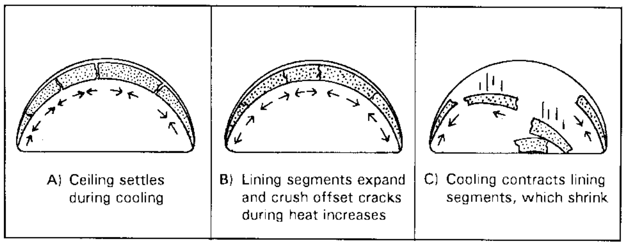

Figure 11. Theoretical promotion of breakdown from thermal fluctuation cycles.

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/cm^3 and 2.0 g/cm^3) 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/cm^3) which had to be buoyant enough to stick up on the wall. This agrees nicely with the 2.33 g/cm^3 and 2.36 g/cm^3 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/cm^3 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

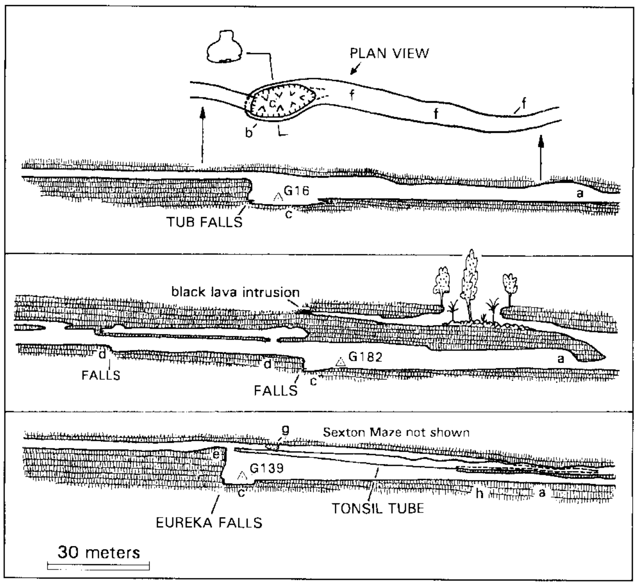

Figure 15. Some projected profile views of typical lava falls. Sexton portion. (a) beginning area of backcutting, (b) secondary passage width enlargement, (c) plunge pool, (d) the development of a stepped floor with any significant slopes taken up by falls, (e) lip build-up, (f) primary widening, (g)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

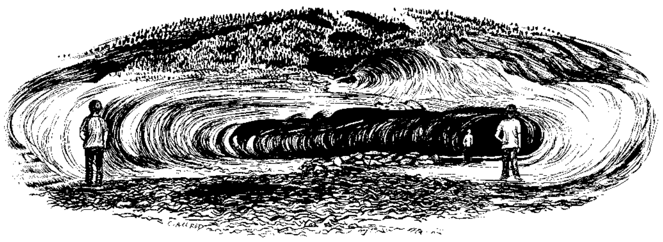

Figure 19. Low, wide passages are often found where the gradient is nearly level. Exaggerated widths as this are most common under the coastal plain in the Lower Kazumura portion. View is upstream. Drawing of a photo by K. Allred.

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. Re-insulation 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.

ACKNOWLEDGMENTS

We would like to thank the participants who helped with the survey of Kazumura Cave, especially Mike Shambaugh. Mike also collected most of the specific gravity samples. William R. Halliday reviewed an early draft, and Ronald Greeley contributed some important references. Mahalo to all the helpful Hawaiians.

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INITIAL GEOLOGIC OBSERVATIONS IN CAVES BORDERING THE SIBARI PLAIN (SOUTHERN ITALY)

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Geologic investigation of caves in the northern Calabria region of Italy has clarified their origin and irregular distribution. Caves and surface karst landforms are not widespread, despite the fact that the local limestones are widely exposed and surface drainage is poorly developed. The caves are located in small limestone hills and mountains around the Sibari Plain and are surrounded by low-permeability rocks. Among them is a significant shaft cave fed by a sinking stream that drains a non-karst recharge area. However, most of the caves are predominantly horizontal and have entrances at low altitudes at several levels. Their origin is due to the rising of thermal waters, which are mineralized after passing through the Neogene formations of the Sibari Plain. The caves can be considered relict hypogenic outflow caves. The main cave-forming process was probably the oxidation of H_2S, favored by the mixing of thermal water and infiltrating fresh water. Oxidation of H_2S has resulted in gypsum deposits within the caves.

GEOLOGIC SETTING

The tectonic and stratigraphic evolution of the northern Calabria region is very complex, and in the study area a great variety of rocks can be recognized, from Alpine to Apenninic in origin. A major transform fault (Sangineto Line) divides igneous and metamorphic rocks in the south from the mainly sedimentary rocks in the north (Figure 1).

The sedimentary cover has been chaotically folded by collision between the European and African tectonic plates (Amodio M. et al., 1976). The lower part consists of thick limestone and dolomite deposits of Triassic through Cretaceous age overlain by Paleocene and Miocene calcarenites and marls. The carbonate unit is overthrusted by the Liguride Complex, which consists of unconformable ophiolite-bearing marine sequences, shales, and turbidites of Late Jurassic to early Miocene age (Bonardi et al., 1988).

Tectonic uplift continued during the Miocene, and the Apenninic mountain chain became almost completely emergent above sea level. Marine sedimentation continued only around the perimeter of the mountain chain, where terrigenous facies accumulated (claystones, sands, and gravels). Thick gypsum and salt beds were deposited during the Messinian.

During the Pliocene and lower Pleistocene, marine conditions prevailed only in the Sibari Plain, which formed a small gulf within the Apennines chain. A clay and sand succession accumulated in this area to thickness as great as 1000 m. In the middle Pleistocene the entire area became emergent, and alluvial terrace gravels reached 100 m thick.

GEOMORPHOLOGY AND HYDROLOGY

The northern Calabrian region is characterized by mountains rising to more than 2000 m (e.g. Mount Pollino, 2267 m), which descend steeply toward the Mediterranean Sea. Limestones and dolomites are widely exposed throughout the mountainous area west of the Sibari Plain. To the north, in contrast, low-permeability rocks of the Liguride Complex predominate, and small isolated limestone hills are surrounded by non-carbonate rocks. Also, within the Sibari Plain are scattered limestone hills partly buried by the thick terrigenous Neogene sequence.

The abundant precipitation and extensive limestone exposures have combined to produce a well-developed underground drainage. Many springs are located around the mountain chain, where the low-permeability Neogene deposits have buried the carbonate rocks, and in the vicinity of major faults. Most of these springs consist of calcium bicarbonate waters with low temperatures ranging from 4 to 17º C, depending on

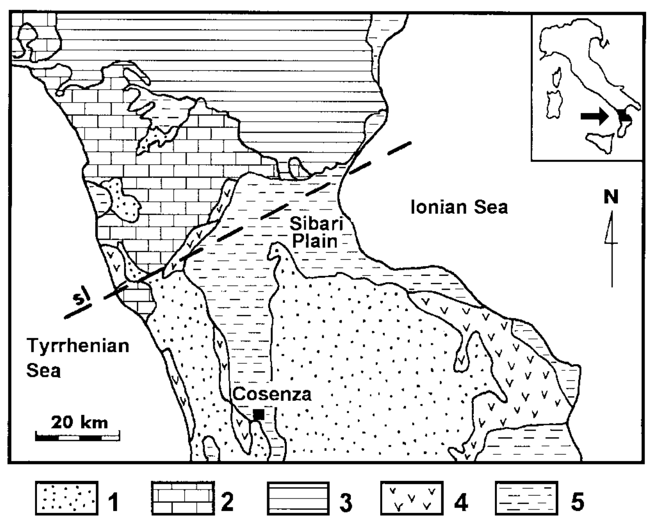

Figure 1. Geologic map of northern Calabria (Italy) 1 = igneous and metamorphic rocks; 2 = limestone and dolostone; 3 = Liguride Complex (low-permeability rocks); 4 = Miocene deposits; 5 = Plio-Pleistocene deposits; sl = Sangineto Line.

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Figure 2. Entrance of Grotta delle Ninfe. This is the main sulfur spring in the Mount Sellaro area. The water emerges at 28° C and is used in nearby thermal baths.

Figure 3. Surface karst landforms on Mount Sellaro (1439 m msl). The main caves of northern Calabria are located in this mountain. The bare landscape and the general lack of surface drainage are typical characteristics of the karst in this area.

their altitude. They are fed by meteoric waters coming from the uplands through a shallow underground circulation.

However, around the Sibari Plain, there are also thermal springs (23 - 40º C) with sulfate-chloride waters rich in H_2S. Despite their high temperature, their isotopic signatures demonstrate a meteoric origin (Gurrieri et al., 1984). These thermal springs are located near the edges of the Sibari Plain at the base of the isolated limestone hills described above (Figure 2). Also, Duchi et al. (1991) do not believe in a deep origin of these waters; for these authors the weak thermal characteristics could derive from a rapid rise of meteoric waters that have infiltrated into the limestone uplands and that follow a relatively deep circulation path. This deep circulation and the rising flow paths in the downflow ends should be facilitated by the high hydraulic heads in the rugged uplands and by the presence of major faults. The chemical composition of the water is probably derived from mixing with connate water and by dissolution of evaporites within the Neogene deposits of the Sibari Plain.

CHARACTER OF THE CAVES

Surface karst landforms and caves are fairly rare in the extensive carbonate outcrops, despite the rugged topography and the lack of a well-developed surface drainage. The paucity of karst features cannot only be attributed to limited exploration of the area, which began in the 1960s. However some large caves, described in detail by Larocca (1991), are known in the isolated mountains and hills of the Sibari Plain (Figure 3). Their geomorphic and hydrologic characteristics will be briefly analyzed.

ABISSO DEL BIFURTO

This shaft cave, explored in 1961, is one of the deepest in southern Italy. Its entrance is located on the west side of Mount Sellaro at 920 m msl. It consists of a pit series (Figure 4) interrupted by short meandering canyons that reach 680 m deep, close to the local base level (springs at 200 m msl). The

Figure 4. A typical scene in the shaft cave Abisso del Bifurto.

cave clearly originated as the result of the partial sinking of a surface stream at the boundary between the low-permeability rocks of the Liguride Complex and the underlying Cretaceous limestone (Figure 5). The cave is still active (Figure 6), but the recharge area for the sinking stream on the non-karst rocks appears to have been reduced by piracy into neighboring valleys.

SERRA DEL GUFO CAVES

Many caves have developed in the eastern side of Mount Sellaro at 200 - 500 m msl (Figure 7a). Their entrances are located near the transform fault that forms the tectonic boundary between the Carbonate rocks on the southwestern side of Mount Sellaro and the low-permeability Liguride Complex. The lower caves reach the phreatic zone and are notable for their sulfur-rich water, which has temperatures varying from 28º C at the springs to 40º C in the bottom of the "Balze di Cristo" cave, a 100 m deep shaft that reaches the water table. Within these caves gypsum replacement crusts form on the limestone walls above the water table as the result of H_2S oxidation.

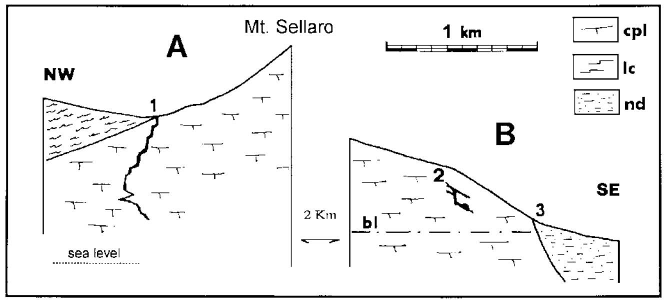

Figure 5. Schematic cross-section through Mount Sellaro. A = Abisso del Bifurto area; B = thermal spring area. Abisso del Bifurto feeds the Mount Sellaro aquifer, but there is probably no direct karst connection between the cave bottom and the thermal sulfur spring. cpl = Cretaceous and Paleocene limestone; lc = Liguride Complex; nd = Neogene deposits; bl = present base level; 1 = Abisso del Bifurto; 2 = Grotta di Serra del Gufo; 3 = thermal spring.

Figure 6. Entrance of Abisso del Bifurto. After heavy rainfall a surface stream draining from non-karstic rocks floods the cave.

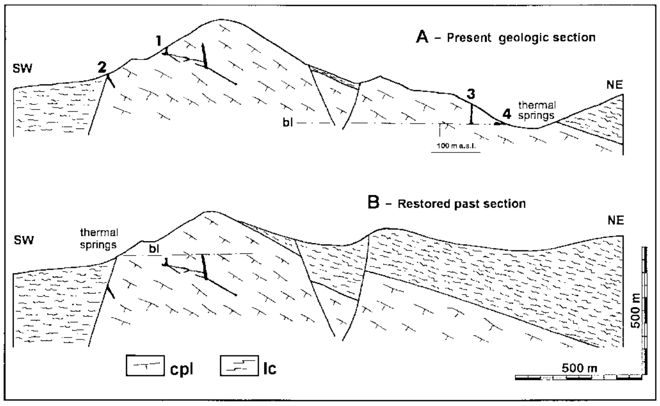

Figure 7. A = cross-section through the southeastern side of Mount Sellaro, showing the present caves and geology; B = interpretation of conditions during previous cave development. Note the denudation of the limestone surface and the migration of springs as surface streams erode to lower levels. Cpl = Cretaceous and Paleocene limestone; lc = Liguride Complex (low-permeability rocks); bl = base level; 1 = Grotta di Serra del Gufo; 2 = Damale cave; 3 = Balze di Cristo cave; 4 = Ninfe cave.

The main cave (Grotta di Serra del Gufo, about two kilometers long) is a relict cave containing inclined passages that rise toward the land surface (Figure 8). The cave pattern is strongly controlled by the dip of the limestone and by faults. Phreatic tubes are common (Figure 9), but breakdown and carbonate speleothems have obliterated many of the original features. The cave also contains some gypsum deposits. The upper passages reach approximately 550 m msl, which probably represents a former base level (Figure 7b). This level also corresponds to alluvial gravel terraces of middle Pleistocene age on the nearby Sibari Plain.

CASSANO ALLO JONIO CAVES

Cassano allo Jonio is a small town situated near a steep isolated limestone hill surrounded by low-permeability strata of the Liguride Complex and the Neogene terrigenous sequence. The most important caves (e.g. Grotte di Sant' Angelo) open at about 450 m msl in a steep slope along the main fault. Altogether these caves are more than 2000 m in length. They consist of several sub-parallel horizontal passages at slightly different elevations, which intersect a large room (Figure 10). These caves are characterized by abundant gypsum deposits, which were partly quarried away in the past. A sulfur spring is located at the foot of the limestone hill at 200 m msl.

DISCUSSION

The irregular distribution of caves in northern Calabria is clearly controlled by geologic factors. There are no significant caves in the extensive high-altitude carbonate mountain chains, but caves are abundant in the narrow limestone outcrops along

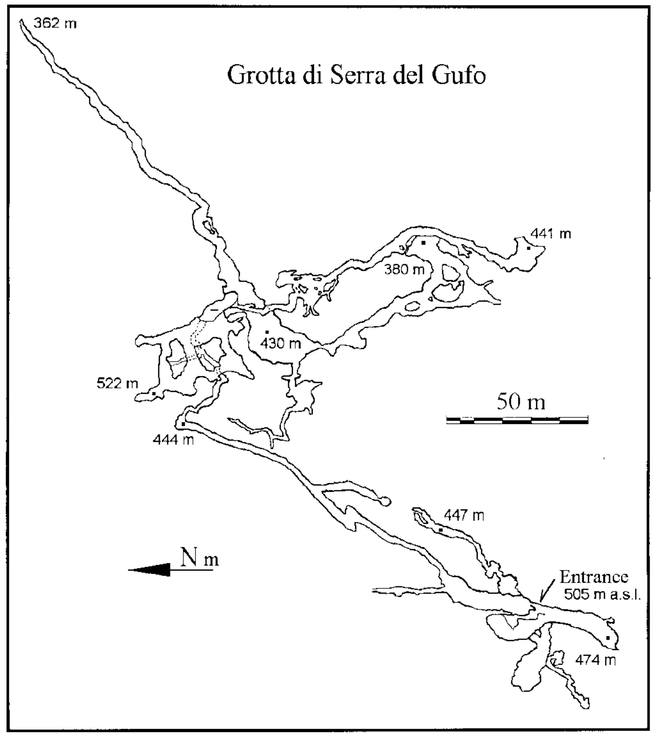

Figure 8. Map of Grotta di Serra del Gufo, the largest cave in the study area (survey by the Sparviere Speleological Group).

the edges of the Sibari Plain (Figure 11), despite their relatively small recharge areas and small relief. Shaft caves are rare throughout the area, with Abisso del Bifurto the only significant exception. Sub-horizontal caves are the most common and are concentrated at low altitudes in the sides of the limestone hills and mountains around the Sibari Plain (e.g. Cassano allo Jonio caves) or rise toward the outer edges of the mountains (Serra del Gufo caves). Abundant gypsum was formed

Figure 9. Grotta di Serra del Gufo consists of relict passages, mostly steeply inclined, with phreatic characteristics.

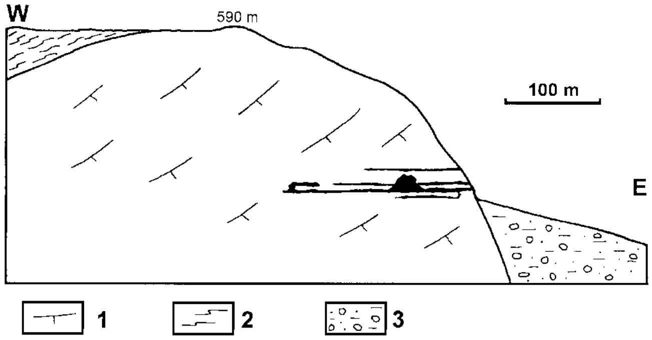

Figure 10. Schematic cross-section through Grotte di Sant' Angelo, at Cassano allo Jonio. 1 = Triassic dolomite; 2 = Liguride Complex; 3 = Neogene deposits.

during the cave origin as the result of sulfide-rich water flow, and sulfur springs fed by phreatic water are still present at low altitudes.

The cave features, limited recharge area, and the lack of connection with the rare influent caves preclude an origin by shallow meteoric water. On the contrary, the rising of H_2S-rich water within the limestone seems to be the principal cave-forming agent. The chemical characteristics of the waters, the hydrogeologic setting, and the gypsum deposits suggest that the oxidation of H_2S to sulfuric acid is the main source of solutional aggressiveness. This redox reaction and the mixing with fresh meteoric water descending along faults probably occurred in the upper part of the phreatic zone. Deepening of surface drainage channels interrupted the cave development, leaving relict gypsum-rich caves at several levels, while cave-forming processes began to operate more deeply toward the present base level.

This hypogenic origin can also explain why the major caves in northern Calabria do not occur in the largest carbonate massifs. The thermal, H_2S-rich waters rise only in the narrow karstified limestone belts around the Sibari Plain, where mixing with superficial calcium bicarbonate waters is possible.

ACKNOWLEDGMENTS

I wish to thank Larocca Felice (Calabrian Speleological Cadastre) for his help and for providing the photographs in this paper. I also thank Arthur Palmer, for the encouragement to write this paper and for having kindly re-worked the English, Donald G. Davis and Margaret Palmer, for their revisions, which helped to clarify the text.

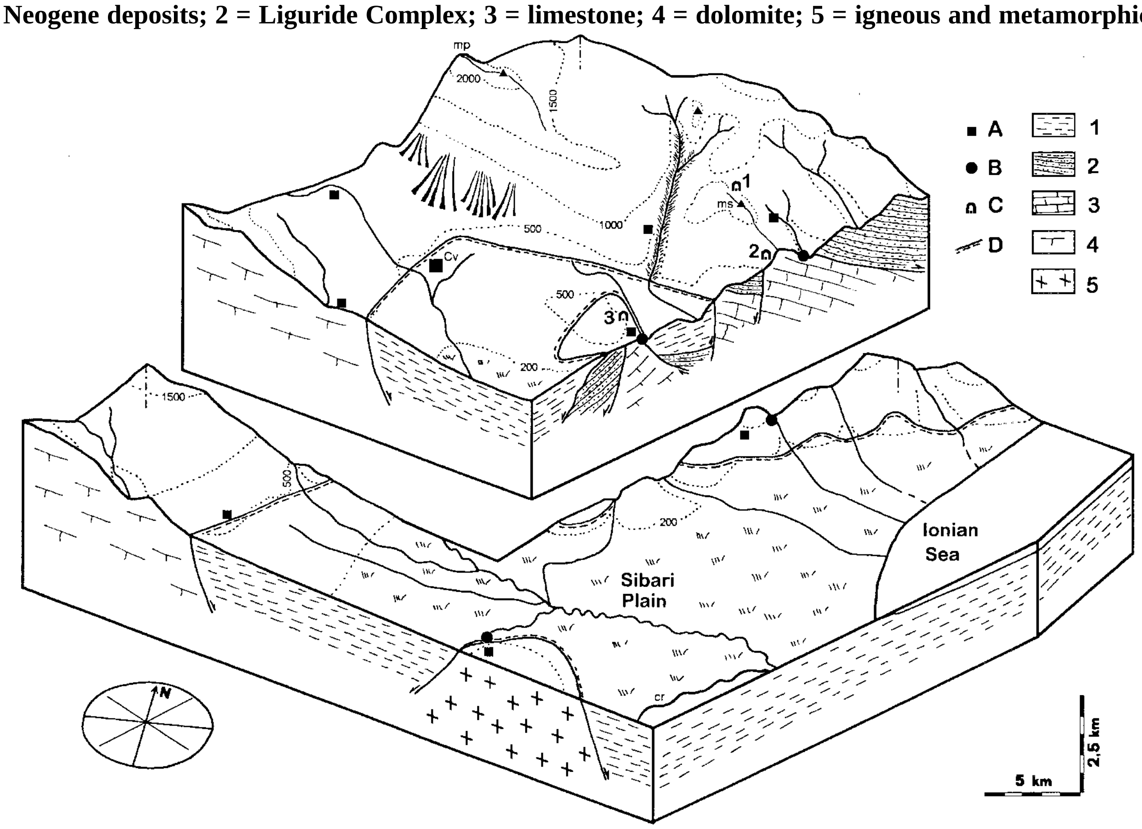

Figure 11. The extensive limestone and dolomite outcrops in the mountain chain permit well-developed underground drainage. Thermal water, mineralized in the Neogene formations, rises around the Sibari Plain in small limestone massifs, where hypogenic caves originate. An allogenic shaft cave opens at the boundary between the limestone and the low-permeability cover. 1 = Neogene deposits; 2 = Liguride Complex; 3 = limestone; 4 = dolomite; 5 = igneous and metamorphic rocks;

A = town (Cv = Castrovillari); B = thermal spring; C = caves 1 = Abisso del Bifurto; 2 = Serra del Gufo caves; 3 = Cassano allo Jonio caves; D = boundary of Neogene deposits; mp = Mount Pollino; ms = Mount Sellaro; cr = Crati River.

V.A. Maltsev.-A Model of Structure and Genesis for the Gypsum "Nest" Found in the Geophysicheskaya Cave (Kugitangtou Mountains, Turkmenistan). *Journal of Cave and Karst Studies* 59(2): 87-90.

A MODEL OF STRUCTURE AND GENESIS FOR THE GYPSUM "NEST", FOUND IN THE GEOPHYSICHESKAYA CAVE (KUGITANGTOU MOUNTAINS, TURKMENISTAN)

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A description, and a possible structure and genetic mechanism for a "gypsum nest", a very rare speleothem consisting of gypsum needles growing from a drying clay massif, are considered. Because of conservation concerns, theoretical modeling is the only acceptable method for studying this complicated and delicate feature. The model suggested considers the "nest" as a screw-dislocated spherocrystal, with its sub-individuals separated by corrosion at some initial stage, and having separate growth at later stages.

EDITORS' NOTE: Some mineralogical terms that are not in common use in the English literature are defined at the end of this paper for the use of the reader.

The speleothem, referred to as a "nest" (Figure 1), is known from only one location in the world, in the Geophysicheskaya Cave, Kugitangtou Mountains, Turkmenistan. All of the main features of the nest are known in other types of speleothems. There are also apparently reports of similar phenomena found in Lechuguilla Cave (Guadalupe Mountains, USA) (D. Davis, pers. comm.). The nest and similar features are not believed to be the result of external physical conditions, but are more likely the result of some mechanism related to crystal growth.

Of course, these speleothems are too rare, too beautiful, and too delicate to be considered for study by direct methods (i.e., collecting). Given this, I offer the following description, along with suggestions (based on theoretical modeling) for the structure and genesis of the nest.

Figure 1. The gypsum "nest" from the Geophyszicheskaya cave. Photo courtesy of Alexander Samoilov.

DESCRIPTION

The "nest" is located on a large flat massif of alluvial clay, that is currently undergoing a drying episode. A part of this massif, tens of square meters in area, where the air circulation is apparently optimum for efflorescence, is entirely covered with various gypsum needles, "hedge-hogs", and "cotton" masses. These are varieties of filamentary crystals and fibrous aggregates, known to crystallize from plastic substrates. The "nest" itself appears as a funnel-shaped mass of thousands of oriented gypsum needles with a hollow interior. The needles are approximately 0.1 - 0.5 mm thick, up to 40 cm long, and twist counter-clockwise around the axis of the "funnel". The diameter of the complete construction is about 30 cm, which makes it stand out from the surrounding gypsum crystal fabrics, that, in turn, are characterized by shorter, thicker, and chaotically oriented needles. The central hole of the nest is also funnel-shaped, and has one needle situated along its central axis. The "nest" grows on a relatively flat floor, and is tilted about 20º relative to the floor.

POSSIBLE STRUCTURE AND GROWTH MECHANISMS

The crystallization mechanism of filamentary crystal crusts, growing from drying clays (Maleev, 1971; Maltsev, 1996; Stepanov, 1971), can have only a spherical symmetry. Other factors, such as local air circulation, humidity, and clay porosity, may cause the formation of aggregates and crusts which are not truly representative of ideal growth of the crystal. So, we must search for the source of the "nest's" symmetry not on the levels of crusts or aggregates, but on the level of individual crystals. Here we deal not with texture symmetry,

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but with structure symmetry, and it may be controlled not only by mass-transportation factors, but also by crystallization physics.

In a monocrystalline case the most probable reason for such regular twisting is a screw dislocation of the crystallographic framework. Counterclockwise dislocation, as seen in Figure 1, is usual for gypsum (Hill & Forti, 1986). Screw crystals on this clay massif are rare, and so their appearance in such great numbers in one particular spot must be due to some special circumstance.

The hypothesis that is most sound invokes the origin of the nest from a single splitted screw crystal. This explains the two main morphological features of the "nest": (i) regular twisted needles [the screw dislocation is generalized upon the whole splitted crystal], and (ii) the longer crystals that stand out from the surrounding materials [screw crystal growth speed is normally greater than usual crystal growth speed (Grigorgev & Zhabin, 1975; Hill & Forti, 1986; Maleev, 1971)].

Still, several features remain unexplained. For example, filamentary crystals (the base for needles) always grow from their roots outward, and poorly connected spherolite bunches usually grow on their outer heads.

As indicated by other researchers (Casali & Forti, 1969; Maleev, 1971; Maltsev, 1996; Stepanov, 1971), filamentary sulfate crystals growing from drying cave clays have the following properties: a) near the crystal "root", there is a zone of splitted growth, and after it - a zone of skeleton growth, that are controlled by physics; b) when these zones are overlapped, dendritic needles appear in full accordance with the definition of Grigorjev and Zhabin (1975), that a dendrite is a splitted skeletal crystal; c) if the splitting rate is high, needles with properties of spherocrystals appear - with full generalization of the crystallographic network properties upon all the speleothem (Godovikov, et al., 1989; Grigorjev & Zhabin, 1975); d) in places experiencing intense seasonal humidity cycles, the roots of the gypsum needles are usually corroded.

DISCUSSION

With the establishment of the above properties, we can now consider the conditions that could lead to crystallization of a speleothem such as the "nest" (Figure 2). From the above cave conditions and the crystal properties, we can hypothesize the following sequence of events:

1) A splitted gypsum crystal, having properties of a spherocrystal, and not yet extruded from the surface. Because of this, the splitted zone covers its entire length. As shown by Maltsev (1996), the 400%-500% relative oversaturation needed for gypsum crystal twinning (Russo, 1981) is possible. The capillary pressure in the pores of the clay is dozens of atmospheres, and the needle physically blocks the pores, pressing out the solution from between them. When reaching the needle surface, where the pore is enlarged and the capillary pressure is lower, the solution becomes oversaturated due to the pressure change. There are no theoretical restrictions on the existence of such needles with screw dislocations. Moreover, the "antholite-like packets", described by Maltsev (1996) and also known as "gypsum grass" (Hill & Forti, 1986), in reality are splitted needles with screw dislocations, formed in very similar conditions.

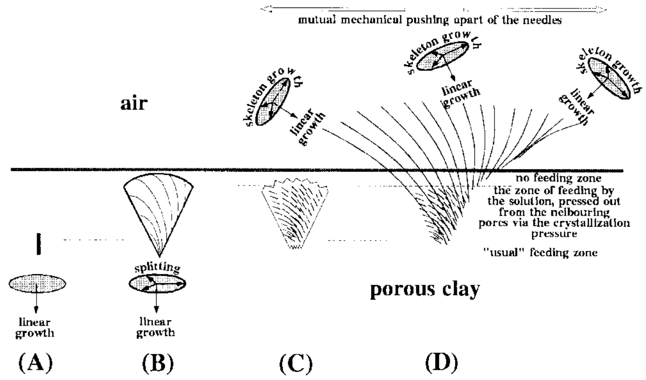

Figure 2. Genetic scheme for crystal aggregates such as the "nest". A. a screw-dislocated filamentary crystal. B. its splitting up to a spherocrystal. C. its partial dissolution with disconnection into acicular relicts. D. their independent growth with mutual mechanical interactions.

2) Flooding, causing 30-50% dissolution of the needle. The corrosion-sculptured forms for spherolites and spherocrystals are widespread and well-known, though not clearly described in the literature. When the spherolite center and its outside surface are equally exposed to the corrosive solutions, the spherolite separates into radial needles - relicts of sub-individuals. The author has studied many such corrosional effects on gypsum spherolites found in caves. These radial needles that are produced by the partial dissolution of the spherolites due to occasional flooding of the clay sediments are formed in place in the clay. The relict needles would be disconnected, but held in place by clay.

3) Restoration of dry conditions, and along with this, reactivation of the needle growth. Given the phenomena above, the relict needle of each packet would serve as an inception point for the new needle growth. And all of them would have the same screw dislocation as the source needle had.

However, there is a difference between the original growth and restored growth. Now we have multiple objects in the feeding zone, suited for one object. With this, the concurrent selection is already impossible - the zone, where the needles could block each other, is already behind. So, the supersaturation of the solution remains, but very strong deficit of solution appears. This leads to limitations in the needles' thickness increase, and to this increase going exclusively through the crystals skeletization, without further splitting.

4) A restricted thickness increase, caused by the above, will change the morphology of the packet. Their divergence angle,

between 5 - 10º originally, will increase, thus converting the packet from having geometry of a cone to having geometry of a hyperboloid of one sheet (akin to an object such as the Eiffel Tower). During this phase, the needles would be mechanically aligned to directions of generatrixes of this hyperboloid.

5) When the needles are extruded through the surface, they retain their orientation from (4) with only one additional change - that caused by curving under their own weight.

In the above I have proposed a genetic and structural model for speleothems such as "nests". Although speculative due to the non-invasive nature of my investigation, this model is realistic and simple enough to be accepted as a working hypotheses. Some other (not screw) bushes of oriented needles, may be also explained through this concept of splitting, dissolution, and growth re-activation.

ACKNOWLEDGMENTS

I would like to acknowledge the members of my caving team, who initiated this study by their questions. I also appreciate the efforts of Victor Polyak and Ira Sasowsky in making this article more understandable for English-language readers, who are using different axiomatics and terminology.

DEFINITIONS (OF TERMS NOT IN COMMON USE IN THE ENGLISH LITERATURE)

ANTHOLITE

Somewhat similar to the term "flower". The difference is that "flower" may be applied to separate branches, and "antholite" always refers to the whole aggregate, usually having several branches. When used as "antholite crust" it refers to the all the filamentary efflorescences in a given crystallization episode at a locality.

SKELETON CRYSTALS, SKELETON GROWTH

When the crystallization environment is highly supersaturated, but with weak feeding or weak mixing, the crystallization process becomes unbalanced. The crystals grow rapidly, but the media cannot provide enough space to accommodate massive crystals. This unbalance makes crystal growth concentrate on edges or apexes, barely constructing some edges. The result is a crystal, constructed of needles along edges with nothing between them, or a crystal, having faces, but empty inside, etc. In the English literature these formations are usually referred to either as regular twinning, or as dendrites. Both interpretations are incorrect, because skeleton crystals are true monocrystals, growing from a single nucleus, just in peculiar environments. Skeleton crystals are not mineral aggregates, but mineral individuals - single crystal objects.

Dendrites are somewhat similar formations to skeleton crystals. They also require the same unbalance in the environment, but also need some splitting factor. Dendrites are characterized by permanent splitting of skeleton crystals during growth, and/or additional nucleation.

SPHERICAL SYMMETRY, SPHEROCRYSTALS, SPHEROLITES

In the onthogeny of minerals the concept of characteristic symmetry of mineral bodies is of central importance. The idea of the characteristic symmetry of some natural phenomena, defined as maximum possible symmetry, consistent with the existence of these phenomena, was first suggested by Curie, then was carried into mineralogy by Lemmlein. Another concept used is dissymmetry, defined as a single symmetry element, missing or possible raising the characteristic symmetry of an object to the next level.

This concept is very useful. It can be applied to irregular objects, that MAY be regular, and tend to be regular. We cannot see characteristic symmetry completely (like crystallographic symmetry), but we always can see its traces. Here appears the first use for this concept - it can be applied not only to trivial objects and phenomena, but also to higher organized objects-not only to crystals, but also to aggregates, crusts, etc.

The main use of this concept comes from the Curie symmetry principle. If some mechanism or process has some consequence, then the consequence's characteristic symmetry or dissymmetry is some projection of the mechanism or process's symmetry (dissymmetry). Characteristic symmetry may be found not only in material objects, but also in properties of environments. Knowing this, we can find connections between the mass-transportation symmetries and dissymmetries of the crystallization environments, and structure and texture symmetries and dissymmetries of the crystallization products. The last can be also used in reverse, for identifying crystallization environment properties required for growth of a given mineral body.

The characteristic symmetry is usually referred to in terms of a geometric shape having a particular needed symmetry, such as cylinders, cones, or spheres. This is easier than operating with mathematical descriptions. For example, spherical symmetry for a mineral aggregate means that individual crystals have no preferential growth directions, unless if caused by mechanical obstacles.

SPLITTING, SPLITTED GROWTH

Mineral bodies, starting as a single crystal, and then converting into a "packet" of "crystals", bending apart one from another, are well-known, and may be seen in any museum. In Western mineralogical thought they are usually taken as "crystal groups" or something like that.

In reality they are single crystals with a single nucleus and contiguous growth, but a splitted crystallographic network. If we take a splitted crystal of quartz, we will see that all of the sub-individuals are left, or all are right-never mixed. This is because they are not separate crystals, but separate heads of one crystal.

Crystal splitting may occur for several reasons and may go to several splitting grades. The most common reasons for splitting are:

a) Microscopic mechanical inclusions (also possible from the same mineral). They leave "shadow holes" in the crystallization front, allowing the crystallization forces to push apart separate zones of crystal, thus bending the crystallographic network.

b) Extra molecules appearing in some layers of the crystallographic network. This usually comes from solutions that are highly supersaturated, but not so oversaturated as to cause spatial nucleation.

c) Structural admixtures of an ion with different radius than the main one. In reality this leads to the (b) case, because the larger or smaller ion does not lead to regular increase of the molecular quantity from layer to layer, but provides "weak places" for inserting additional ions even without high supersaturation. For example, admixture of Mg or Sr in calcite makes splitting much easier.

Some minerals are hard to split, some easy. Under usual cave conditions it is almost impossible to find splitted gypsum, or to find unsplitted aragonite. But in unusual conditions it may be the opposite.

Mechanical splitting (a) may produce only objects of low splitting grade, where sub-individuals are separated and have faced heads-clusters, sheaves, etc. Typical cases of rough splitting, that can be seen in any museum-stilbite sheafs, or kyanite clusters. The other two mechanisms (b,c) may provide higher grades of splitting (as well as low grade).

When the sub-individuals are seen only as fibers, and have no faced heads, we speak of spherolites (straight fibers), or spheroidolites (bent fibers). Both are distinctly different from radial-fibrous aggregates. The latter have an internal core and multiple mineral individuals around them (usual or splitted), aligned through geometrical selection. The most common example of spherolites are globular chalcedony formations.

When splitting reaches the highest grade, all boundaries between fibers disappear-splitting goes on almost at the molecular level. The crystallographic network totally generalizes upon the entire object, together with all of its properties. If with rough splitting the faces of crystal heads are straight, the cleavage is usual, etc., in the high grade case, we can see curved crystal faces, spherical cleavage, etc. Such formations are called spherocrystals. The most typical example is malachite spherocrystals, widely found in ore deposits.

All splitted crystals, as with skeleton crystals and usual crystals, are not mineral aggregates, but mineral individuals - single crystal objects.

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M. Susan Duncan-Examining Early Nineteenth Century Saltpeter Caves: An Archaeological Perspective. *Journal of Cave and Karst Studies* 59(2): 91-94.

EXAMINING EARLY NINETEENTH CENTURY SALTPETER CAVES: AN ARCHAEOLOGICAL PERSPECTIVE

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During the War of 1812, the southeastern United States experienced a drastic need for saltpeter to be used in gunpowder. The limestone caves of Kentucky became the focal point of a brief, but vital, mining industry. Two production models are drawn from the extant literature and compared to Saltpeter Cave, an archaeological case study site in northeastern Kentucky. Equipment types, production systems, and water-transport systems are discussed vis-à-vis their function in each production model.

In the early part of the nineteenth century, Kentucky led the southeastern United States in saltpeter production. Many of the state's limestone caves proved to be quite prolific sources for this critical ingredient of gunpowder. The arid conditions necessary for the presence of nitrates have also resulted in the excellent preservation of much of the equipment used in the mines (For a discussion of the origin of nitrates in limestone caves, please see Lewis, 1992, and a reply by Hill, 1992.) It seems that in many saltpeter mines when the war was over and the price of saltpeter plummeted, the miners literally dropped their tools where they were standing and left the caves. Given this unique behavior and the high state of preservation, surprisingly little archaeological research has been done at these sites. At Mammoth Cave, an architectural inventory has been completed of the extant saltpeter works, but most of the archaeological research conducted has focused on the prehistoric mining and other prehistoric components.

Some work has been conducted in terms of the origin of cave saltpeter (Lewis 1992; Hill 1992, 1981a, 1981b). It is not this author's intent to enter that debate. Instead, this article examines the operation of saltpeter mines, their equipment types, and their productivity. This paper discusses the results of archaeological investigations conducted at Saltpeter Cave (also referred to as 15Cr99, this site's unique archaeological number assigned by the Office of State Archaeology in Kentucky) in Carter Caves State Resort Park in northeastern Kentucky (Figure 1). Two models of saltpeter mines are drawn and discussed in terms of the case study site.

Most saltpeter caves display three basic categories of extant features: heavy soot deposits, large piles of spoil dirt, and casts of leaching vats. Not all of these categories are apparent in every saltpeter mine and, therefore, evidence of nineteenth century activity can be tenuous at times. Soot deposits and spoil dirt may be evidence of prehistoric rather than historic mining episodes (Munson et al., 1989). Another problem with sites from the early nineteenth century is that more often than not, there are few, if any, documents that refer to the mining operations. Therefore, we must rely on the archaeological evidence in order to discern the history of the site.

The question from these tenuous, empirical data, then, is can we discern any systematic, region-wide patterns of the 1812-era saltpeter industry? Many mines were in operation simultaneously. Were they operated in a similar manner? Previous work in 1812-era saltpeter caves has implied that there were only two types of mining operations and that each system tolerated only a small range of variation in equipment construction.

The first model (Type A) is the large-scale production system. Mammoth Cave and Great Saltpeter Cave are two of the best-known examples of this type (Figure 1). The large-scale system used leaching vats of the box type that held many tons of dirt. A large number of people were employed in the operation, and a complex water-transport system was used. For example, at Mammoth Cave a pump tower and water pipes were constructed to move water from remote areas to the hoppers (De Paepe, 1985). The miners at Type A sites were retrieving calcium nitrate from the cave sediments. This deliquescent form of nitrate had to be converted to potassium nitrate, so a conversion step was added to the production process.

The second model (Type B) involved small cottage-industry operations, which were most often located in rockshelters.

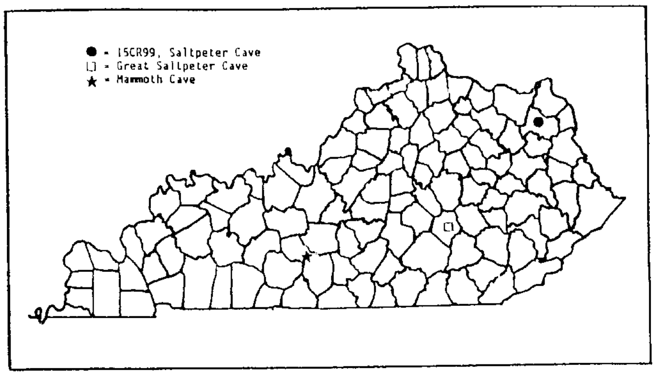

Figure 1. Map of Kentucky indicating locations of three major early nineteenth century saltpeter caves.

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Typically, these operations were located near water sources and used a V-vat type of hopper. The rockshelters were quickly exhausted of their nitrate deposits, and the V-vats were easily dismantled, moved to the next rockshelter and reused. Often, these mines yielded potassium nitrate and since there was no need for a conversion step, as in the Type A systems, these were less complex in their organization. Type B systems are also found in small caves, in which calcium nitrate was being mined. The scale of the production system in use was partially due to the particular substance being retrieved. The major factor affecting the type of production system, however, was the size of the cave. Each production system was modified somewhat to adjust to the working room available at each site.

Each production stage required different types of equipment. In Type A systems, necessary equipment included: those objects and tools involved in water transport; leaching vats; smaller tools such as mattocks, shovels, ladles, paddles, buckets, and hoes; and boiling kettles. The amount and variety of equipment involved suggests a complex system. Type B systems did not involve many tools, so few were left behind as the miners exhausted one site and moved to the next. Often the only signs of mining activity at Type B sites are tally marks, spoil piles, and occasionally casts of V-vats. These casts are rare, however, as the vats were typically dismantled and moved from shelter to shelter.

One of the requirements of the lixiviation of saltpeter from cave earth is an abundant supply of fresh water. Type A systems devised a variety of solutions to obtain water for processing the soil. At Mammoth Cave the miners installed a pump tower and complex water pipe system within the cave. At Great Saltpeter Cave, a pump tower was used to bring water from the creek below the entrance of the cave up the hill and into the cave where the leaching vats were located. Most Type B sites were located adjacent to a water supply, and water was probably transported in buckets.

How does the archaeological evidence from Saltpeter Cave compare to these models? Saltpeter Cave has a surveyed distance of over 2700 m and has passages of both walking and crawling height (Figure 2). Unlike the typical Type A caves, Saltpeter Cave does not have enormous trunk passages with ceiling heights of more than three meters. In the areas of the heaviest mining activity in this cave, the ceiling height has been reduced by nearly 60 cm due to the dumping of spoil dirt on the floor. Today the ceiling height is between 1.8 to 2.4 m. These relatively low ceilings did not allow for the construction of the large vats that are found at Mammoth Cave and Great Saltpeter Cave. On the other hand, there was more than enough room to construct vats on a slightly larger scale than those at the transient Type B rockshelter sites.

Vat types have been employed in the past as diagnostic artifact types. As noted earlier, Type A operations used primarily large, box-shaped vats that could hold tens of tons of earth, while the rockshelter operations used V-vats (De Paepe, 1985). However, the case study site, Saltpeter Cave, has a totally different type of vat (Figures 3 & 4), combining features of both Type A and Type B containers. Like Type A vats, these contain sideboards that are horizontal, rather than like the vertical board-and-batten sides of Type B vats. Like Type B vats, the water trough is placed beneath the vats, and the Carter Caves hoppers have a slight V-shape. They have an average volume of approximately one cubic meter, closer in size to type B vats than to Type A vats. However, Type B operations generally seem to have used only one or two vats per site. The primary operation at Saltpeter Cave involved more than 25 vats. Three of these represent post-1814 mining episodes. The remainder of the existing observable vats, and others that the miners subsequently buried beneath spoil dirt piles, were most likely used in pairs.

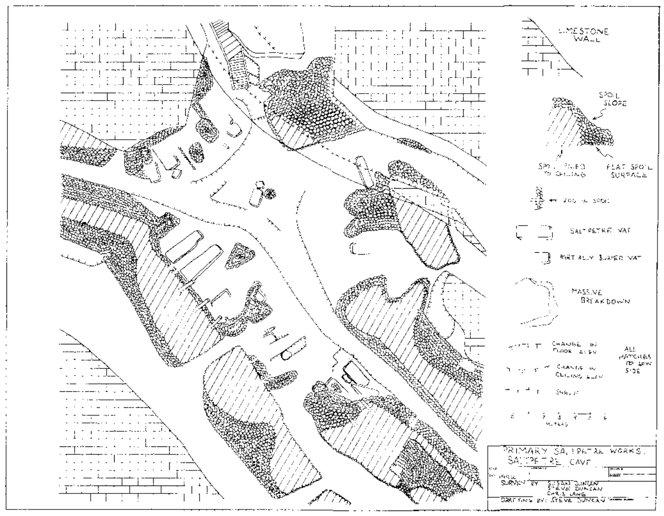

Figure 2. Map of Room A in 15Cr99, Saltpeter Cave. This is the major area of mining activity. Map by Steve Duncan.

Pairs of vats have been identified in Saltpeter Cave and the individual members seem to have been functionally related. Each half of a pair is closer to its partner than to any other vat, and its dimensions are more similar to its partner than to the rest of the vats. Each half is oriented in the same direction, while neighboring vats are placed at different angles. Finally, structural links have been found that connect the pairs. This partnership between vats is not completely understood, but the most likely hypothesis is that one vat was filled with sediments that were being leached, while fresh cave earth was being mined and placed in the second vat. This would have been made for more efficient use of the vats and of the labor involved, and would have produced a more concentrated leachate.

There are also indications of a water transport system at Saltpeter Cave that involved pipelines. Like the pairing of vats, the water transport system has not been thoroughly investigated, but it appears to have been more complex than those employed by Type B systems. Type B miners moved water from nearby streams to the vats in buckets. However, at Saltpeter Cave, the closest water source of any volume is locat-

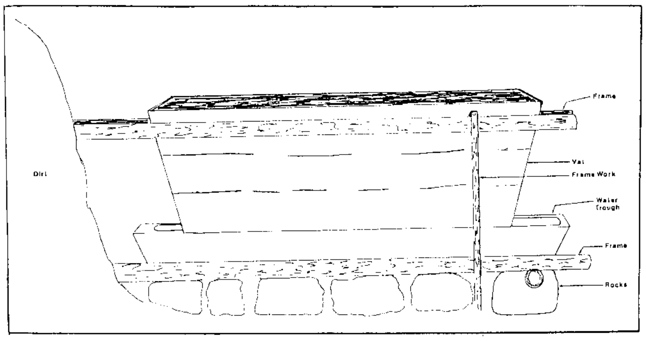

Figure 3. Side view of author's reconstruction of one leaching vat from 15Cr99, Carter Caves vat style. Artists: Paul J. Tierney and Heather Marek.

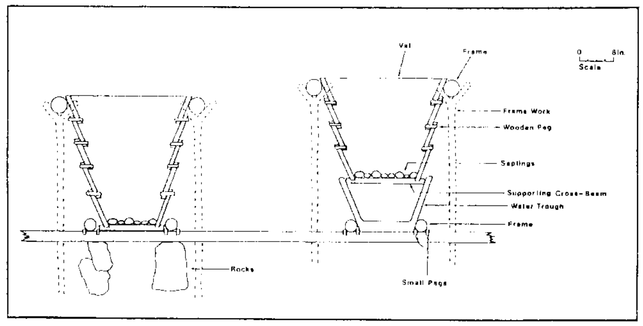

Figure 4. Cross-section of author's conception of a leaching vat pair from 15Cr99, Carter Caves vat style. Artist: Heather Marek.

ed outside and over a hill below the cave entrance. Hauling water in buckets at least 200 m uphill to the entrance and then down another 50 m to the leaching vats would have been quite expensive in terms of time, labor, and yield. There are sections of small wooden troughs or pipes that may have been used to move water uphill or through the cave. This resembles those systems used at Type A mining operations.

Saltpeter Cave was potentially one of the top two producers of saltpeter in Kentucky during the War of 1812. Mammoth Cave was the other major producer, the production at Great Saltpeter Cave having greatly diminished by 1811. Although the cave does not have the great size of Mammoth or Great Saltpeter Caves, it seems to have been a highly productive mine, based on soil analyses and comparison with the results of the 1981 mining experiments at Mammoth Cave (Eller, 1981).

At Saltpeter Cave, at least 620 cubic meters (17,200 bushels) of earth were processed. Applying the Mammoth Cave yield of between three and five pounds per bushel of cave earth (Eller, 1981) to the operation at Saltpeter Cave gives us a range of between 51,600 and 86,000 pounds (23,400 and 39,000 kg) of saltpeter. Kentucky's total production of saltpeter in 1812 was over 312,000 pounds (142,000 kg) (De Paepe and Hill, 1981). In other words, Saltpeter Cave at Carter Caves had the potential to have produced 29% of the total output in 1812, in a state that had more than 200 saltpeter caves and rockshelters. During the height of the war, saltpeter was selling for 75 cents to $1.00 a pound ($1.65 to $2.20 a kilogram). The operation at the Carter Caves Saltpeter Cave, then, could have potentially generated at least $38,000 during the War of 1812. These numbers indicate that this site was one of the highest producers of saltpeter during the War of 1812.

After the war, it appears that the mine at Saltpeter Cave changed from a major, organized industry to a small, cottage industry production system. Stated another way, it seems that there was a transition from a Type A production site to a Type B production site, as the result of a drastic change in the market. Following the conflict, the price of saltpeter dropped from between 75 cents and $1.00 per pound to 15 cents per pound (33 cents per kilogram) (Kleber, 1992). At that time, the Carter Caves area was part of a large land grant. No individuals are named in the earliest deeds, so we do not know who were the owners and/or operators of this mine. If local farmers became miners during the war, they must have been working together in a cooperative, or working for the actual owner of the mine. Once the war ended, presumably they returned home.

There are indications in the cave that limited, sporadic mining events occurred after the war. This evidence includes two V-vats that are separate and distinct from the more typical Carter Caves vats described earlier. These V-vats resemble Type B vats and they are different in size, construction, and preservation from the majority of the vats in this cave. These V-vats suggest that the local farmers-former miners-occasionally returned to the cave to mine saltpeter, presumably for their own use. This activity is suggestive of cottage industries. They could have used the saltpeter to make their own gunpowder, cure meat, pickle food, or for medicinal purposes.

So, what can we infer about 1812-era saltpeter mines as a regional industry? The evidence seems to indicate that rather than two discrete types of saltpeter production (i.e., large- and small-scale operations) each with its own specific kinds of equipment, a variety of production techniques were employed. Miners probably heard about successful techniques in other caves and adopted what seemed to best fit their specific cave environment. While saltpeter caves shared a basic production technology, the equipment and operation of each mine was unique. Production was not limited to any particular type based on the size of the cave.

I have considered archaeological evidence such as spoil dirt piles, casts of leaching vats, and wooden artifacts among other data in an attempt to understand the operation of 1812 saltpeter mines. The data exist and are still available (although conditions at each site are generally deteriorating due to modern site use). Archaeological research can be employed to gain increased awareness and understanding of the history of these caves before they are forever and irrevocably damaged. Additional research will lead us to further understanding of this early nineteenth century industry that must have drastically, if briefly, changed the economy in many rural areas of the southeastern United States.

ACKNOWLEDGMENTS

I wish to thank everyone who reviewed early drafts of this paper, including Steve Duncan, Will Holmes, Jason Griffey, and Linda Forman. Paul J. Tierney and Heather Marek drafted the figures. John Tierney, Sam Plummer, and Harold Plummer offered invaluable assistance and advice throughout the project. Thanks also the many other friends and professors who offered help and advice, and to the anonymous reviewers of this article. I would also like to thank the Sara Corrie Memorial Exploration Fund and the National Speleological Society Research Committee for two grants to conduct the archaeological research that led to this paper and others.

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CAVE SCIENCE NEWS

KARST MEETING PLANNED AT MAMMOTH CAVE

A joint meeting of the International Geological Correlation Program, Project 379: "Karst Processes and the Global Carbon Cycle" along with Friends of Karst will take place on September 23, 24, and 25, 1998, at Mammoth Cave, Kentucky, USA. The meeting will be hosted by the Center for Cave and Karst Studies at Western Kentucky University, Mammoth Cave National Park, and the Cave Research Foundation.

Preliminary plans are to have two days of scientific presentations on various aspects of karst science, with particular sessions so far anticipated on progress in understanding the impact of karst processes on carbon cycling at a variety of scales, and on recent work in the Central Kentucky Karst. A third day will be planned for a variety of surface and subsurface field trips in and around the Mammoth Cave System, which at a current surveyed length of over 560 km is the world's longest known cave.

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LETTER TO THE EDITOR

Since the submission of our paper, "Development and Morphology of Kazumura Cave, Hawaii," it has come to our attention that others have independently and recently described the importance of re-insulation of lava tubes near entrances, downcutting, and back-cutting of lava falls. Readers are referred to the following references for further reading on the subject:

Buchas, H. (1996). Differenzierung der Lavaflusse der Ai-laau Schildphase des Kilauea, Hawaii im Gebiet von Keauhou Trail anhand von Lavarohren und Obrflachenmophologie. Dipl. Kartierung, FB Geowiss., Techn. Univ. Darmtstadt, 58 pp, unpublished. (German)

Hartmann, J. (1995). Keauhou Cave System im Keauhouflow auf Hawaii. Dipl. Kartierung, F B Geowiss., Techn. Univ. Darmstat, 74 pp, unpublished. (German)

Kempe, S. (1996) Enlargement of lava tubes by downcutting and breakdown. *Abstracts and Proceedings of the National Speleological Society Convention 58*(3): 203.

Kempe, S. (1996). Neue Rekorde in Lavahohlen auf Hawaii, ein Statusbericht. Mitt. Arge f. Karstkunde Harz e.V. 1996(3): 46-49 und (mit gleichem Text) Lavahohlen auf Hawaii ein Statusbericht. Mitt.Verb. Dt. Hohlen- u. *Karstforscher 42* (2): 27-29. (German)

Kempe, S. (in press). Lava Falls: a major factor for the enlargement of lava tube of the Ai-laau shield phase, Kilauea, Hawaii. *Proceedings of the 10th International Congress of Speleology*. Switzerland.

Kempe, S., Buchas, H., Hartmann, J., Oberwinder, M., Strassenburg, J. & Wolniewicz, K. (in press). Mapping lava flows by following their tubes: The Keauhou Trail/Ainahou Ranch Flow Field, Kilauea, Hawaii. *Proceedings of the 10th International Congress of Speleology*. Switzerland.

Kempe, S. & Oberwinder, M. (in press). The Upper Huehue Flow (1801 eruption, Hualalai, Hawaii): An example of interacting lava flows yielding complex lava tube morphologies. *Proceedings of the 10th International Congress of Speleology*. Switzerland.

Kempe, S. & Ketz-Kempe (in press). Archaeological observations in lava tubes on Hawaii. *Proceedings of the 10th International Congress of Speleology*. Switzerland.

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BLACK HILLS KARST AQUIFER

Readers interested in the caves of the Black Hills in South Dakota will want to check out the September-October 1995 issue of *Ground Water 33*(5). Earl Greene's and Perry Rahn's paper, "Localized Anisotropic Transmissivity in a Karst Aquifer" describes the general geology of the area. They also relate trends of cave maps, fracture patterns and joint patterns to local, directional permeability of the limestone. (Thanks to Mike Hanson for sending us this information.)

GUIDE TO AUTHORS

The *Journal of Cave and Karst Studies* is a multidisciplinary journal devoted cave and karst research. The *Journal* is seeking original, unpublished manuscripts concerning the scientific study of caves or other karst features. Authors do not need to be members of the National Speleological Society but priority is given to manuscripts of importance to North American speleology.

Languages: Manuscripts must be in English with an abstract, conclusions, and references. An additional abstract in another language may be accepted. Authors are encouraged to write for our combined professional and amateur readership.

Content: Each paper will contain a title with the authors' names and addresses, an abstract, and the text of the paper. Acknowledgments and references follow the text.

Abstracts: An abstract stating the essential points and results must accompany all articles. An abstract is a summary, not a promise of what topics are covered in the paper.

References: In the text, references to previously published work should be followed by the relevant author's name and date (and page number, when appropriate) in brackets. All cited references are alphabetical at the end of the manuscript with senior author's last name first, followed by date of publication, title, publisher, volume, and page numbers. See the current issue for examples. Please do not abbreviate periodical titles.

Submission: Authors should submit two copies of their manuscript (include only copies of the illustrations) to the appropriate specialty editor or the senior editor. Manuscript must be typed, double spaced and single-sided. Authors submitting manuscripts longer than 15 typed pages may be asked to shorten them. Authors will be requested to submit an electronic copy of the text, a black-and-white photograph, and brief biography of the author(s) upon acceptance of the paper.

Discussions: Critical discussions of papers previously published in the *Journal* are welcome. Authors will be given an opportunity to reply. Discussions and replies must be limited to a maximum of 1000 words and discussions will be subject to review before publication. Discussions must be within 45 days after the original article appears.

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Process: All submitted manuscripts are sent out to two experts in the field. Reviewed manuscripts are then returned to the author for consideration of the referees' remarks and revision, where appropriate. Revised manuscripts are returned to the appropriate associate editor who then recommends acceptance or rejection. Upon acceptance, the author should submit all photographs and original drawings to the editor.

Once the paper has been formatted and laid-out, the senior author will be sent one set of proofs for review. Any corrections, other than printer or editor errors, will be done at the author's expense. Examine the current issue for more information of the format used.

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