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THE ORIGIN OF TUBULAR LAVA STALACTITES** AND OTHER RELATED FORMS

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ABSTRACT

Tubular lava stalactites are often found in lava tubes. Field observations, sample analysis, and comparative studies indicate that these are segregations extruded during cooling from partially crystallized lava at about 1,070 - 1,000 °C. Retrograde boiling (gas pressure) within the lava provides a mechanism to expel the interstitial liquid. In addition to tubular lava stalactites, a variety of other lava features can also result, such as lava helictites, lava coralloids, barnacle-like stretched lava, runners, runner channels, and some lava blisters and squeeze-ups.

Keywords: lava speleothems, soda straws, experimental growth

INTRODUCTION

The study sites for this paper are four lava tubes totaling approximately 71 km of mapped passages located on Kilauea volcano, Hawaii (Fig. 1). Here, as in other well preserved lava tubes we investigated in Hawaii and the western United States, interior surfaces are commonly coated with "a thin, smooth, vitreous surface" known as glaze (Larson, 1993). This is sometimes underlain by a variable layer of dark-hued rock on either broken or smooth surfaces. Where thick, the dark deposits are usually associated with slender, worm-like lava stalactites (Fig. 2,3). These are called tubular lava stalactites, and can be straight, branching, eccentric, or even deflated. Their interiors are usually an entrainment of elongated vesicles and septa, but some examples are completely solid or hollow (Larson, 1993). Where these stalactites drain, globular stalagmites might be built (Fig. 2,3). Previous investigators have theorized these stalactites originated from: 1. water vapor (Dana 1849, Brigham 1868, Dana 1889), 2. remelt (Jaggar 1931, Hjelmqvist 1932, Perret 1950, McClain 1974, Baird, Mohrig and Welday 1985), and 3. other means (Williams 1923, Harter 1993, Favre 1993, Ogawa 1993, Allred 1994).

METHODS

Some tubular lava stalactites and ceiling lining samples were crushed and then tested for grain density using kerosene as a displacement medium. Eight thin sections were made of stalactite and ceiling lining samples. X-ray analyses were done on a Philips X-

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[**] After the submission of the paper, the Authors regrettably decided to print it in the "Journal of Cave and Karst Studies", Vol. 60, n. 3: 131-140.
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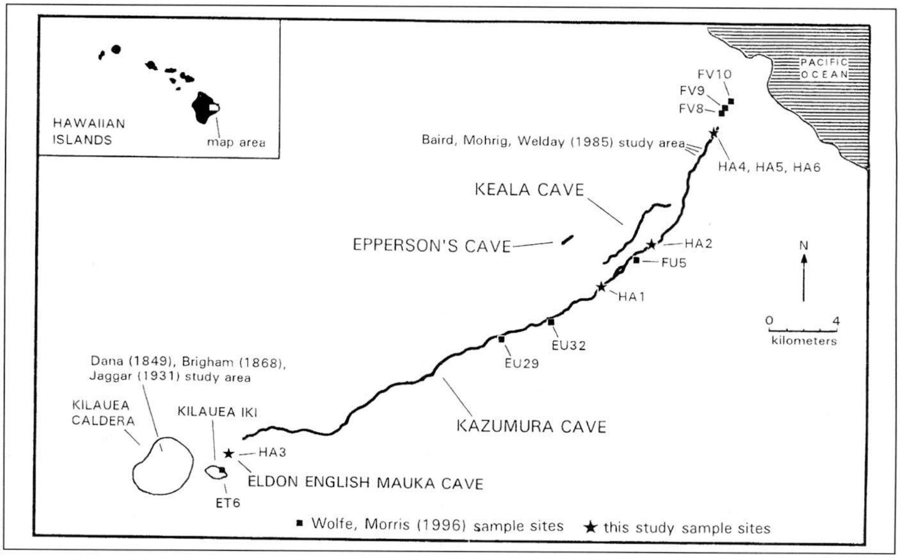

Fig. 1. study caves. Keala from S. Kempe, (pers. comm.). Eppersons from W.R. Halliday (pers. comm.). Kazumura and Eldon English Mauka Caves after Hawaii Speleological Survey (NSS) files. Bulk rock samples from Wolfe and Morris (1996).

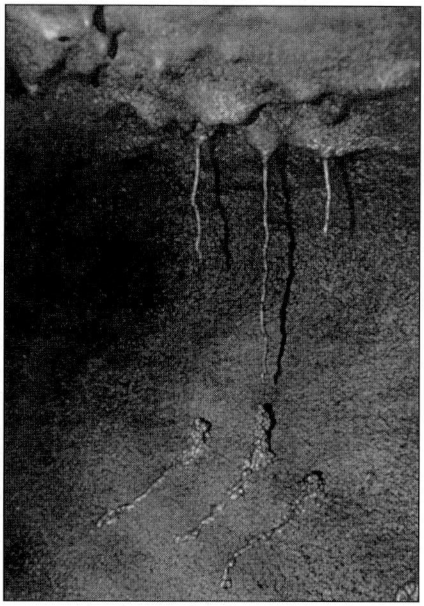

Fig. 2. Tubular lava stalactites, stalagmites and runners. The Marriage Passage (an extraneous lava tube) in Kazumura Cave. Photo by Mike Shambaugh.

ray diffractometer for modal composition. Chemical analyses of 69 elements were made of a group of small tubular lava stalactites and the parent lining 1 - 3 cm above the stalactites. This was done primarily by ICP-AES (inductively coupled plasma emission spectrometry), INAA (instrumental neutron activation analysis), ICP/MS (inductively coupled plasma-mass spectrometry), and XRF (X-ray fluorescence spectroscopy).

Field observations in 1995 and 1996 were correlated with paraffin models used to simulate tubular lava stalactite growth. A caldron of liquid paraffin drained through a coarse filter, valve, and tube, into a small cooling reservoir. The paraffin then seeped through a sponge filter and out a final tube. Temperature was monitored with thermometers in both containers.

DISCUSSION

Field observations give us some clues as to the origins of tubular lava stalactites and related forms. In some instances it can clearly be seen that their fluids originated from within the rock itself, as manifest by tiny conduits directly above their uppermost portions. Most tubular lava stalactites we found tended to be eccentric and kinky nearer their ends (Fig. 3). Others had formed only as an incipient coralloid shape (Halliday, 1994). They are called runners (Larson, 1993) where they are found against a surface

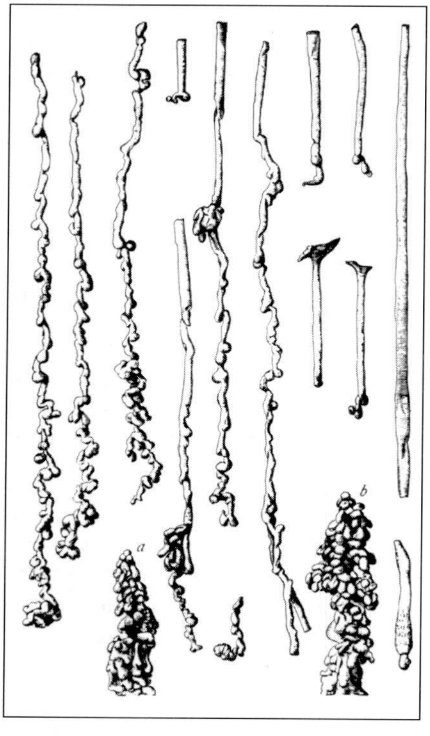

Fig. 3. Tubular lava stalactites and lava stalagmites thought to be from Kaumana Cave near Hilo, Hawaii (Dana, 1889). The lower ends of the stalactites tend to be more eccentric. As is typical, stalagmites show signs of more fluidity nearer their bases.

Fig. 4. Squeeze-up, Keala Cave. This erupted lava is suspected of being extruded in a similar fashion to tubular lava stalactites. The battery above the rounded cap is 5 cm long. Photo by Carlene Allred.

(Fig. 2). If runners flowed down a tubular lava stalactite, the original free-dripping portion can be identified by its annular growth rings.

The globular structures of the stalagmites tend to be more runny, and less distinct at their bases (Fig.2,3). The stalagmites were usually deposited after the floor of the tube had stopped moving. Rarely a line of driblets had fallen on a slowly moving floor before a stalagmite was finally formed.

Other kinds of lava features result from extrusions similar to those described above. Dripped "lava roses" (Larson, 1993) can form by falling masses and sheets of lava originating from within ceilings. "miniature volcanoes" (Jaggar, 1931), or "small spatter cone[s]" (McClain, 1974) were forced upwards from ledges or floors. Those we observed often had rounded caps (Fig. 4) and runners around their robust perimeters. Others had crater-like depressions at their tops and resembled miniature volcanos. Lava blisters are sometimes found associated with tubular stalactites and the squeeze-ups. Jaggar (1931) described "barnacle stalactites". We sometimes found these stretched, grooved, forms associated with tubular lava stalactites behind slumped ceiling linings (Fig. 5). They are also common around contracted perimeters of subsided plunge pools.

Concepts of Filter Pressed Segregation

Wright and Okamura (1977) explained that lava can "segregate" from a partially crystallized melt at temperatures between 1,030 and 1,070°(°C). This results in veins of "relatively coarse grained, glassy, vesicular rock" differing in composition from the main body of lava. They aptly describe this process, which is called filter pressed segregation, in lava lakes of Kilauea Volcano:

"The crystal framework of the crust behaves as a filter, through which the liquid fraction moves into the open fracture. The efficiency of the filtration process is variable. Some segregations carry in crystals, so that the bulk composition of the segregation does not lie on the liquid line of descent for the lake as a whole, whereas other segregations are virtually free of early-formed crystals".

Wright and Helz (1987) concluded that highly differentiated segregations can occur in contraction cracks of these lakes between temperatures of 1,060 - 1,000(C, even when interstitial liquid becomes 10% or less. They were inferred to be gas-driven.

We submit that tubular lava stalactites and other related forms are actually segregations ejected by expanding gas into the cave passages. Like the cracks in the cooling lava lakes of Kilauea, some lava tube contraction cracks had been injected with interstitial liquid from both opposing surfaces after they split apart. This material did not come from flowing parent lava of the lava tube. If cracks were widening during the extrusions, stretched barnacle-like forms grew (Fig. 5). It is important to note that the majority of lava tube cracks lack segregations because of improper conditions, or may have opened nearer or below solidus, given as 980°(°C) by Wright and Okamura (1977). Not all extrusive phenomena are filter pressed segregations. For example, settling of crusts may have extruded some parent lava as blisters and squeeze-ups.

Segregation emergence

Why and how did the lava tube segregation extrusions occur only after the lava had reached an advanced stage in crystallization? Rounded bubbles, or vesicles are formed from volatile exsolution at a time when only a small percentage of lava has crystallized.

When 50 to 55% of the lava becomes crystallized at about 1070 °C-1065 °C, it ceases to flow (Wright and Okamura 1977, Peck 1978). This transition is called the crust-melt interface. With more progressed crystallization, interstitial liquids can effervesce between crystal faces to form irregular vugs (Peck, 1978). This is because as crystallization becomes more advanced, volatiles (chiefly H_2O) will be concentrated in the residual melt and retrograde boiling occurs (Best 1995, pg. 246, 292). It is significant that we observed more intense vuggy fabric in linings having higher concentrations of tubular stalactites and other segregations (Fig. 6). In such fabric, vesicle surfaces can become honeycombed with vugs until only their general spherical shapes remain. At least some of the interstitial melt is forced out into the cave to form tubular stalactites (Fig. 7).

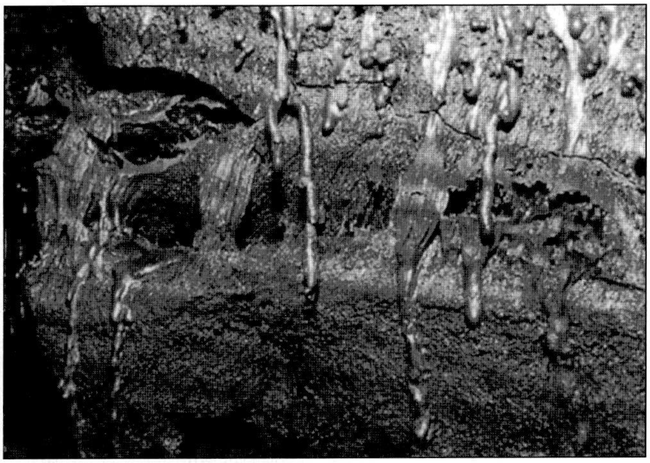

Fig. 5. Barnacle-like stretched lava, Kazumura Cave. Lava forming these was extruded as the crack widened. If the lower part fell away, only the "stalactite" portion remains. Photo by Mike Shambaugh.

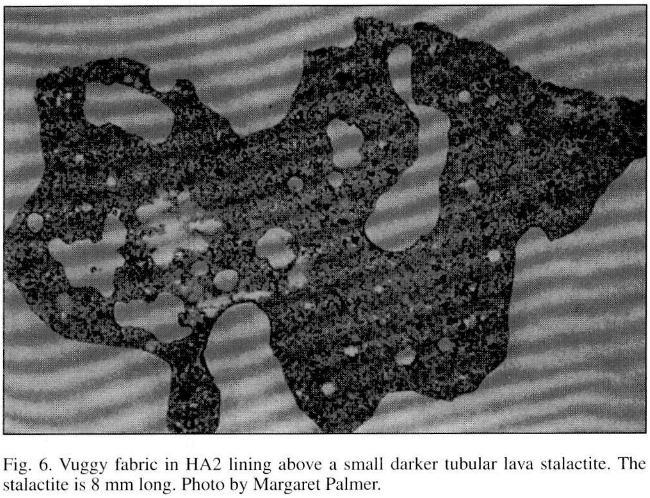

Fig. 6. Vuggy fabric in HA2 lining above a small darker tubular lava stalactite. The stalactite is 8 mm long. Photo by Margaret Palmer.

The occurrence of coarse grains in segregations is evidence of increased diffusion of atoms from high H_2O content. Low viscosity of residual liquid may result from some water molecules combining with O in Si-O tetrahedra to break their chains. Addition of K_2O and Na_2O to silicate melts plays a similar role (Best 1995, pg. 232, 293). With this in mind, we observed a tendency of brownish colored segregation material to have once been very fluid with almost none of the magnetite prevalent in the more common dark gray samples. This may indicate extensive oxidation to hematite under high H_2O conditions that would cause retrograde boiling. Vesiculation in segregations (Anderson et al., 1984) is further evidence that the driving force was retrograde boiling. Even later retrograde boiling can form vugs in tubular lava stalactites and stalagmites to extrude helictites or coralloids (Fig. 8). None of these second order segregations have yet been analyzed.

Comparisons with paraffin models

To help understand the origin of tubular lava stalactites, we were able to simulate their growth using paraffin at approximately 65-70 °C. Paraffin flow was regulated by inserting a sponge plug into the drainage tube which fed the stalactites. This is similar to the process of filter pressed segregation in lava, but where gravity takes the place of gas pressure. The resulting paraffin stalactites were 3 - 4 mm in diameter, and up to 15 cm long. As driblets drained quickly through a stalactite and dripped from the growing tip

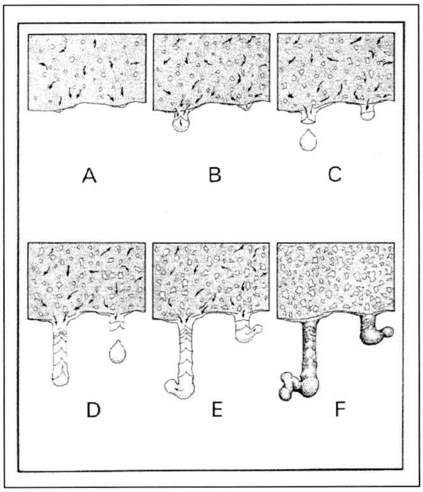

Fig. 7. Proposed extrusion of tubular lava stalactites.
A. Retrograde boiling in the lining creates vugs and begins extruding a thin discontinuous layer of residual melt.
B. Continued residual outpourings collect in some discrete points.
C. Incipient tubular shapes become more apparent, and vugs continue to form in the lining.
D. Continued addition of drip segments creates growth rings. Splitting of the newest skin is perpetuated to additional segments as new driblets emerge.
E. Cooling promotes crystallization of the bottom part of emerging driblets, forcing the liquid to the side or upward into eccentric shapes. Vesicle surfaces have become honeycombed by vuggy fabric.
F. Cooled stalactites.

Fig. 8. Lava coralloids (second-order segregations) extruded from a large lava stalagmite, Eppersons Cave. During the cooling of the lava tube the coralloids formed on the upstream side, and probably leeward of a breeze. The stalagmite is 50 cm high. Photo by Mike Shambaugh.

(Fig. 9), a thin flexible skin extended in segments. We sometimes observed the skins of newest segments splitting open and closing repeatedly parallel to the axis during cyclic driblet movement. This segmenting and splitting is reminiscent of growth rings and linear seams on some tubular lava stalactites.

The paraffin stalactites could be diverted into eccentric directions. Paraffin has high solidification contraction of 14.89% volume. Since the solids will be heavier, they tend to congeal in the bottom of the emerging driblet. The driblet is held to the last segment by surface tension, and the skin is thinnest around the sides of the driblet where spreading is occurring. If the drainage is allowed to cool sufficiently (due to convection farther down the stalactite, or from diminished flow), pressured liquid pushes out or upwards from the side of the driblet, beginning an eccentric form. These breakouts can also occur nearer the attachment point of a stalactite resulting in a compound form. If a breeze is present, preferential growth is leeward. We believe a similar process is involved in the formation of eccentric tubular lava stalactites since lava contracts about 13% (Daly, 1944) (compare Fig. 3, 10). If the paraffin temperature was too hot, a stalactite could not form, and all of each driblet fell into puddles below.

Petrographic Analysis and Density

Our sectioned samples (Table 1) were generally similar to tubular stalactites of previous petrographic studies (Dana 1889, Hjelmqvist 1932, McClain 1974, Baird and oth-

Sample	Olivine	Pyroxene	Plagioclase	Ilmentite	Magnetite	Hematite	Glass, Zeolite[4]	Apatite	Total
HA1 shark tooth stalactite composed of seven linings	?	36.04	31.39	1.16	12.79	1.16	17.44		99.98
HA2 lining portion directly above tubular stalactite		29.16	30.55		15.27	5.55	19.44		99.97
HA2 tabular stalactite portion of sample		16.00	25.00	2.00	19.00	11	27.00[6]		100.000
HA3 both tubular stalactites and portion above are segregations		12.24	16.32		23.46		47.95[6]		99.97
HA4 stalagmite, transverse cross section		32.46	23.37		29.87	3.89	10.38		99.97
HA4 stalagmite, axial cross section		28.41	15.90	1.13	32.96	2.27	18.17	1.13	99.97
HA5 outer portion of HA6, directly above a small tubular stalactite	*	49.99	30.48		12.19	1.22		6.09	99.97
HA5 small tubular stalactite of HA6		39.60	22.77		24.75		8.91	3.96	99.99
HA6 lining from which tubular stalactites had grown	*	66.66	16.00		10.66	2.66		4.00	99.98
Hj[1] tubular stalactite, Raufarholshellir Cave, Iceland		19.00	19.80		7.90	17.90[2]	35.40[3]		100.00
MLL[5] Chemical mode for average Makaopuhi basalt	6.50	39.80	42.50	4.20	1.00		5.00[3]		100.00

Table 1. Modal compositions (volume percent). Segregations are shaded. [1], from Hjelmquist (1932); [2], the outer crust of the stalactite, and includes both hematite and magnetite; [3], all glass; [4], undetermined amounts of zeolite were detected in the glass; [5], uncorrected modes (Wright and Okamura, 1977, Table 14); [6], includes minor amounts of clay deposited on the exterior surfaces of stalactites after they were formed; *, olivine was visible in lining and may have been included in point counts for pyroxene.

ers 1985). The segregations are of darker hue, more coarsely grained, and are higher in magnetite and glass content, than the linings from which they extruded. We found that tubular stalactites can often easily be picked up with a magnet, due to high magnetite content throughout.

Glaze is a <50 micron thick magnetite skin which has a characteristic silver luster from light reflecting off facets of tiny octahedrons. This magnetite ornamentation appears to have grown after the greenish pyroxene-rich surface had begun to crystallize on many lava tube surfaces. We found rare sites of greenish colored linings and tubular stalactites lacking much of the magnetite ornamentation. A reddish color can result when glaze has been oxidized to hematite. The magnetite indicates low temperature crystallization between 1030 °C and solidus (Wright and Okamura, 1977). Thus, we question the prevailing assumption that glaze is evidence of remelt (Jaggar 1931, Peterson and Swanson 1974, Harter 1978, Allred and Allred 1997). As for the darker-hued, coarsely grained, layer sometimes found under some glaze of our samples, this is segregated material. The chemical compositions of tubular lava stalactites and lining above them are found in Table 2. Table 3 shows that many incompatible trace elements are concentrated to nearly 200% in the stalactites. This is another indication that the segregations occurred at about the crust-melt interface. Other elements are compatible with the early formed mineral, olivine, and have lesser concentrations in the stalactites.

In lining/tubular stalactite samples, the transitions between the linings and segregations were much less distinct than between typical layered linings. In the lining/stalactite samples, pyroxene crystals and laths of plagioclase often extended deep into either side of the transition zone, indicating segregation drainage through the crystalline framework.

Runner Channels

Sometimes shallow, incised, "runner" channels are found which extend vertically

Oxide	Tubular stalactite, Kilauea Caldera. (1868)[1]	Tubular stalactite, Kazumura Cave. (1985)[2]	Tubular stalactite HA6, Kazumura Cave. (this study)[6]	Parent lining of tubular stalactite HA6, (this study)[6]	Average parent lava flow. (1996)[3] of the Kazumura		Segregation vein, Makaopuhi Lava Lake. (1977)[4]	Average Makaopuhi basalt. (1977)[3]
					upper flow	lower flow		
SiO_2	51.9	53.3	49.14	48.74	50.70	50.70	50.77	50.18
Al_2O_3	13.4	13.8	12.49	13.70	13.13	13.00	12.27	13.26
Fe_2O_3	15.5		15.33	12.07	12.66	2.87	4.26	1.48
FeO		10.4			--	8.65	10.45	9.86
MgO	4.8	5.5	5.23	8.37	7.85	8.42	4.23	8.27
CaO	9.6	10.9	9.37	11.07	11.33	11.02	8.47	10.82
Na_2O	3.0	2.8	3.05	2.46	2.08	2.10	2.75	2.32
K_2O	1.1	.5	.65	.33	.38	.39	1.11	.54
TiO_2		2.8	3.63	2.08	2.52	2.30	4.49	2.64
P_2O_3			.35	.19	.23	.25	.52	.27
MnO	.8		.20	.17	.17	.20	.20	.17

Table 2. Chemical composition of segregations and Kilauean parent lavas (weight percent). Segregations are shaded. [1], silica oxide and sodium oxide were designated as SiO3 and NaO respectively (Brigham, 1868); [2], collected from Kazumura Cave (Baird, Mohrig and Welday, 1985), total Fe calculated as FeO; [3], from Wolfe and Morris (1996); [4], segregation vein from Makaopuhi lava lake sample 68-2-10 (Wright and Okamura, 1977); [5], Wright and Okamura (1977), Table 12; [6], detection limit of 0.01%.

Element	Au	As	Ba	Br	Co	Cr	Cs	Hf	Ir	Rb	Sb	Sc
detection limit/unit	1 ppb	1 ppm	1 ppm	0.5 ppm	0.1 ppm	0.5 ppm	0.2 ppm	0.2 ppm	1 ppb	10 ppm	0.1 ppm	0.01 ppm
HA6 lining	-2	2	105	-0.5	45.1	695	-0.2	7.6	-1	-10	0.4	29.1
HA6 tubular stalactites	8	2	173	-0.5	42.1	351	-0.2	7	-1	-10	0.7	27.5

Element	Se	Ta	Th	U	W	La	Ce	Nd	Sm	Eu	Tb	Yb
detection limit/unit	0.5 ppm	0.3 ppm	0.1 ppm	0.1 ppm	1 ppm	0.1 ppm	1 ppm	1 ppm	0.01 ppm	0.05 ppm	0.1 ppm	0.05 ppm
HA6 lining	-0.5	0.6	0.7	-0.1	-1	8.4	21	15	4	1.43	0.7	1.76
HA6 tubular stalactites	-0.5	1	1.2	0.5	2	16.9	42	30	7.29	2.46	1.3	3.01

Element	Lu	Sr	Y	Zr	V	Mo	Cu	Pb	Zn	Ag	Ni	Cd	Bi	Be
detection limit/unit	0.01 ppm	1 ppm	1 ppm	1 ppm	1 ppm	2 ppm	1 ppm	5 ppm	1 ppm	0.5 ppm	1 ppm	0.5 ppm	5 ppm	2 ppm
Ha6 lining	0.25	308	23	122	270	3	118	14	87	2.4	151	-0.5	25	-2
HA6 tubular stalactites	0.42	341	41	234	390	3	235	-5	129	2.9	58	-0.5	15	-2

Table 3. Trace and rare earth elements of HA6 lining and stalactites. (-) Indicates below detection limits.

down the cave walls. Those we observed were up to 20 mm wide, 5 mm deep, and up to a meter long (Fig. 11). These "appear" to have been melted into the already solidified walls by hotter lava extruded into the cave through tiny holes in the walls. We believe the volatile-supersaturated segregations pouring from the orifices reacted with the residual liquid of the hot wall lining. This caused some residual liquid to become less viscous and flow away with the segregations. Best (1995, pg. 234) calls this process "depolymerization". In such circumstances, previously crystallized olivine and other minerals would be undermined and wash down the channels with the liquid. Exit holes and internal conduits above the channels seem to have been enlarged as well. Indeed, it may be that "roots" observed to extend above some tubular stalactites (Harter, 1971, 1993) were formed by residual melts depolymerizing along the paths of segregations. As with the other segregated features, the depolymerization occurred during cooling of the lava tube. It is important to emphasize that none of these processes have anything to do with a "remelt" scenario. Although the eventual solidus temperature might be lowered by increased H2O in residual melts, there is no change from crystalline to melt.

CONCLUSIONS

Based on evidence stated above, we conclude that tubular lava stalactites and some other extrusions in lava tubes are filter pressed segregations extruded by retrograde boiling from partially crystallized lava. They occur at or below the crust-melt interface between about 1070 and 1000(C. Segregations differ from their parent linings in density, texture, mineral ratios, and chemical composition. In some cases, segregations depolymerized residual liquid in partially crystallized linings.

Genetically, the outer shells of tubular stalactites function like the insulative linings of the lava tubes in which they grow. The great varieties of these and related features are influenced by composition of the parent lavas, when the segregations occur, the efficiency of filtering, and the complex, open environments under which they cool.

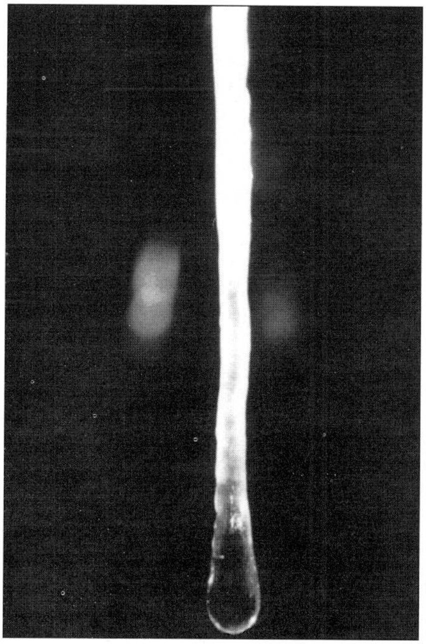

Fig. 9. Tubular paraffin stalactite during growth. The stalactite diameter is 3 mm. Photo by Carlene Allred.

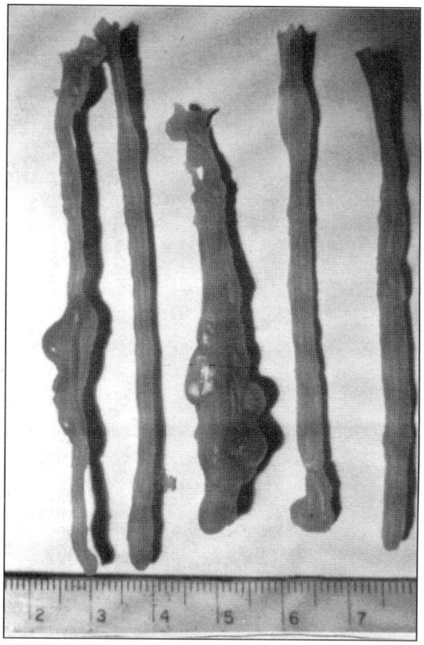

Fig. 10. Some tubular paraffin stalactites. The stalactite diameters are >3 mm. Photo by Carlene Allred.

Fig. 11. Runner channels with subsequent runners, Keala Cave. The scale is 15 cm long. Photo by Kevin Allred.

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