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MORPHOLOGY OF EXTINCT LAVA TUBES AND THE IMPLICATIONS FOR TUBE EVOLUTION, CHAIN OF CRATERS ROAD, HAWAII VOLCANOES NATIONAL PARK, HAWAII

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INTRODUCTION

Studies of active lava tubes have revealed a great deal about the development and evolution of a tube system. However, there are some limitations on the types of data that can be collected from active tubes; parameters such as the thickness and slope of the floor of the tube, for example, cannot be measured on active tubes. Geophysical modeling of tube development has been limited by the lack of data on these and other parameters. A study of extinct lava tubes exposed in road cuts along Chain of Craters Road in Hawaii Volcanoes National Park, Hawaii was conducted to determine the relations between various morphological parameters and provide additional data required for geophysical modeling.

Chain of Craters Road was chosen as a field area because of its accessibility and the large number of tubes exposed in road cuts along its length. This road cuts a number of flows, which, for the purposes of this study, will be divided into Mauna Ulu (1969-1974) and pre-Mauna Ulu flows. The tubes measured formed during rift eruptions of Kilauea. Exposure varies widely along the road, but the tubes measured were relatively evenly split between Mauna Ulu flows and older flows (Figure 1). The tubes measured were also roughly evenly distributed between major, ocean-reaching flows and less extensive flows.

DEFINITION OF TERMS

Lava tubes, which were measured here, were separated from other openings in the lava that have been called "gas blisters" (Walker, 1989) primarily on the basis of surface textures. A lava tube shows clear textural evidence of the passage of lava through ropy texture on the floor, drip structures on the roof, and glazed walls, sometimes with one or more ridges marking a former level of lava (Figure 2A). "Gas blisters," on the other hand, have a uniformly rough, spongy, almost oatmeal-like texture on the interior surfaces. Some have ridges within the rough lava of the floor, indicating that some flow occurred (Figure 2B), and occasionally have ropy pahoehoe flows on the floor while still retaining the rough texture on the walls and roof. They also show concentric zones of vesiculation, with the maximum size and concentration of vesicles increasing towards the center. This vesiculation pattern is very similar to that found in the cross-section of small pahoehoe toes.

When possible, six measurements were made on each tube: height, width, slope, roof, floor, and overburden. These terms are defined below, along with several calculated variables and the criteria for dividing the data on a regional scale:

MEASURED VARIABLES

Height: The maximum vertical dimension of the void in the tube, measured from the top of the floor of the tube to the bottom of the roof.

Width: The maximum horizontal dimension of the void in the tube, measured perpendicular to the long axis of the tube.

Slope: The average slope of the floor of the tube. Slope varies widely within the tubes, changing as much as 15-20° within only a few meters of tube length. As a result, the measured value is somewhat arbitrary and should be viewed as approximate.

Roof: Thickness of the upper crust of the tube, measured from the top of the void up to the bottom of the overlying flow or the ground surface if there is no overlying flow. Where roof thickness varies, the measured value is the average thickness.

Floor: The thickness of the lower crust of the tube, measured from the bottom of the tube void down to the top of the underlying flow, sometimes distinguishable only by the circular vesiculation pattern around the tube. Note that this measurement includes any lava that may have filled in the tube and crystallized as it was draining, and therefore does not necessarily reflect the thickness of the lower crust of the tube when it was still active.

Overburden: The thickness of any overlying flows, measured from the top of the roof up to the ground surface above the tube.

LOCATION AND AGE VARIABLES

Mile: The distance along Chain of Craters Road from the intersection with Crater Rim Drive, measured to the nearest 0.1 mile.

Old: Distinguishes tubes found in Mauna Ulu flows from those found in pre-Mauna Ulu flows.

High slope/Low slope: The high-slope group consists of data from tubes on the Holei Pali, which has slopes of 7-25° (averaging 15°), and the low-slope group consists of data from above and below the pali, with regional slopes of up to approximately 5°.

DERIVED VARIABLES

Floor/roof: The ratio of floor thickness to roof thickness.

Xsect Area: The cross-sectional area of the tube interior, based on the assumption that the tube is elliptical in cross-section with the height and width as the minor and major axes.

AR: Aspect Ratio or the height-to-width ratio of the tube interior.

AR2: Aspect Ratio or the height-to-width ratio of the tube interior approximately accounting for the infilling of the tube. The floor thickness is assumed to be the same as the roof, making the formula AR2 = (Height + Floor - Roof) / Width.

MEASUREMENT ERRORS

Measurements were made to the nearest centimeter. For measurements of height, width, roof, and floor, errors are primarily due to misalignment of the tape. For example, when measuring the width of a tube, the tape might not have been exactly perpendicular to the long axis of the tube, or when measuring the height, the tape might not have been vertical. The magnitude of these errors depends on the size of the tube--larger tubes are more likely to have larger errors. The best estimate of these errors is that for measurements less than a meter, the numbers are accurate to within 2-3 cm, whereas for measurements greater than a meter the numbers are accurate to within 5-10 cm.

The measurements of slope and overburden are less accurate than measurements of the other variables. The slope of a tube can change dramatically over small distances and the floor surface is usually irregular, making the choice of where to measure slope somewhat arbitrary. In addition, the slope measurements are highly dependant on where the road intersects a tube. Therefore, while the measurements themselves are accurate within 1°, they should be considered representative of the tube near that point only within 10°. Overburden was often difficult to measure, and was estimated to within 50 cm on the larger outcrops.

DISCUSSION OF RESULTS

A total of 177 tubes were measured for this study (see Table 1). The tubes ranged from 8 to 160 cm in height and 28 to 420 cm in width and had roofs between 4 and 110 cm thick and floors between 9 and 130 cm thick. Overburden measured from 0 to 8 m thick. Local slopes range from 2 to 32°.

Of that total, 32 tubes were in the "low slope" category and 145 were in the "high slope" category; Thirty-nine were in pre-Mauna Ulu flows. Although these distinctions were made during data gathering, subsequent statistical analysis showed that these sub-populations were not distinguishable.

The standard deviation of the variables is uniformly high, approximately 2/3 of the average values. The averages generally fall into the smaller end of these ranges, showing that the population in this study is predominantly made up of small tubes. However, the distribution of values of all parameters showed a decidedly positive skew between 1.1 and 2.15. The computed averages were generally greater than the central tendency of the distribution. This suggested to us that the distributions were more log-normal than normal and the statistics were recomputed for a log-transformed values (also shown in Table 1). Log-normal averages were much more representative of the central tendency of the values and had significantly reduced skewness of -0.328 to 0.295. The standard deviation of these distributions were more uniform being between .235 and .281 (multiplicative factors of 1.72 to 1.91) suggesting a more representative distribution for all the parameters.

Table 1. Average values and standard deviations for variables. %SD expresses the standard deviation as a percentage of the average value.

	Height	Width	Slope	Roof	Floor	Ovrbrdn	Fl/Rf	Xsect Area	AR	AR2
TOTAL										
Average	39	127	9.8	21	32.8	127	1.98	5018	0.35	0.47
SD	28.5	91.9	6.06	13	22.1	156	1.27	7182	0.2	0.25
%SD	76	72	62	62	67	123	64	143	57	53
LOG-TRANSFORMED										
Average	1.501	2.0096	.9125	1.251	1.434	NA	.2278		-.51	
$10^{Average}$	31.7	102.2	8.2	17.8	27.2	NA	1.69		.31	
SD	.281	.280	.253	.271	.273	NA	.259		.235	

CORRELATIONS BETWEEN VARIABLES

Previous studies of active lava tubes on sloping terrain have shown that lava flowing through a tube can cut down into the rock beneath the tube (Jackson and others, 1987; Jackson and others 1988). Studies of active lava tubes forming within sheet flows on relatively flat terrain have shown that lava can inflate the tops of these sheet flows to accommodate tube wall and flux growth

(Kauahikaua and others, 1990). For either process, the height-to-width (aspect) ratio of the tube should increase with time and may be a very rough measure of the degree of maturity of a tube.

Aspect ratio represents the height-to-width ratio of the tube interior. The average aspect ratios of the tubes studied are in the low end of the range (0.31). Less than 3% of the tubes measured have an interior height greater than the interior width (Figure 3). The observation that as a tube system evolves preferred pathways develop which concentrate the flow into a few major tubes infers that, in any cross-section of a flow field, younger tubes would be more plentiful than older tubes. The preponderance of low aspect-ratio tubes in the Chain of Craters road cuts, together with the above notion of tube evolution from many small tubes to a few large tubes, shows that young tubes probably have low aspect ratios.

The majority of tubes measured had floors which were thicker than their roofs (Figure 4); the average floor-to-roof ratio is on the order of 1.7 (see Table 1). Because the floor measurement includes any infilling of the tube that may have occurred, this ratio probably does not reflect the true floor-to-roof ratio of the tubes when they were active. Another factor contributing to this high average ratio is variations in the lava level in the tube. The level of lava within a tube might often be too low to accrete material onto the roof, especially towards the end of activity; therefore, the floor may continue to grow while the roof may not grow at all. On the other hand, theoretical studies of cooling coupled with temperature measurements suggest that either the roof and floor crust grow at approximately equal rates or that the floor crust grows at a somewhat slower rate (75% in Hon and others, 1991).

The possibility of tube infilling just before extinction probably biases our calculations of the aspect ratio towards low values. To evaluate this hypothesis, aspect ratios were recalculated by assuming that the tube floor thickness is equal to the tube roof thickness using the formula

$$AR2 = (height + (floor - roof)) / width$$

The mean recalculated aspect ratio was somewhat larger the original mean value, but they are still less than 0.5 and still indicate a tendency for tubes that are wider than their height.

Plots of other variables (for example, aspect ratio versus cross-sectional area) revealed little in the way of correlations. Assuming that subsurface flow eventually becomes concentrated into a few major tubes, it seems likely that the long-lived tubes, which must accommodate the bulk of the flux of lava, would become the larger tubes. However, plots of aspect ratio (presumably increasing with age) versus cross-sectional area show no clear correlation (Figure 5). In fact, in plots of AR versus cross-sectional area, the few tubes with aspect ratios greater than one appear to have relatively small cross-sectional areas. This is probably due to inadequacy of the sample size; if most of the flow is concentrated into only a few major, long-lived tubes, large tubes should be relatively rare and the likelihood of encountering them in the area sampled is small.

REGIONAL VARIATIONS

Variations based on regional slope can be seen by comparing the low-slope group to the high-slope group (Table 1). The first obvious difference is the number of tubes found in each area. The high-slope part of the road covers about 5 miles of the 23 miles of road studied. However, this five-mile part contained 81% of the tubes measured. A conclusion that high-slope area produce more tubes than low-slope areas is suspect, however, because the number of outcrops is dependent on the amount of cutting into the ground that was done during road construction. Building a road in a high-slope area necessitates more cutting into the surface in order to maintain a low grade than does construction of a road in a low-slope area.

Regional slope also appeared to have little or no correlation with size of the tubes. It might be expected that tubes would decrease in size with increasing slope; a higher regional slope would lead to higher slope within a tube, which in turn would lead to a greater lava velocity. If true, this means that a given volume of lava per time period could pass through a smaller tube and this greater lava velocity suggests that the floor of the tube would be eroded more quickly, leading to a higher aspect ratio. However, plotting cross-sectional area versus slope yields no correlation (Figure 6A). In addition, the slope appears to have no effect on the aspect ratio of a tube (Figure 6B).

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH:

The vast majority of tubes become extinct while they are relatively small and their aspect ratios are less than one. This observation supports current ideas of tube system development that suggest that a young flow initially forms a number of small lava tubes, eventually concentrating the flow in only a few larger tubes. Although there is no clear correlation between aspect ratio and size of the tubes within this data set, the sample size is insufficient to disprove the supposition that longer-lived tubes are relatively large. There also does not appear to be any simple correlation between the slope (either the regional slope or slope within a particular tube) and the size or aspect ratio of tubes. The relationship between the floor and the roof thickness is not as simple as it might initially seem; that the roof is growing more quickly than the floor is not supported by our data.

There are a number of unanswered questions left by this study. One possibility for further research would be to measure the density of tubes per square meter of outcrop, both in the high-slope and low-slope areas. This would resolve the question of whether there actually are more tubes in high-slope areas or whether the data set has been biased by the relative area of outcrop exposed during road construction.

Another obvious problem is the determination of the true relationship between floor and roof thickness, without the complication of possible infilling. The crust of a tube can often be divided into several crude zones based on vesicle distribution (Figure 2A). Assuming that the lava in the tube as a whole at any given time had the same gas content and therefore left the same pattern of vesiculation in the rock as it crystallized, a band of equal vesiculation that can be traced around the entire tube represents a particular moment in time in the tube's history. Therefore, measurements from both the roof and floor to equal vesicle horizons could simplify our determination of the true relationship between the two variables during the time that the tube was active. Measurement of a few such horizons suggests that the actual ratio between the floor and roof should be much closer to 1.0, but more measurements are needed to verify this result. It would also be useful to measure a number of horizons within a tube, which would possibly provide clues to the evolution of the tube through time.

Finally, a study of the "gas blisters" could determine whether their morphology places constraints on their formation similar to constraints on the formation of lava tubes. Their vesiculation pattern is very similar to that found in small pahoehoe toes, and it seems unlikely that gas pressure alone could be sufficient to support the weight of the roof rocks. It is possible that these structures represent inflation by lava (hydraulic) pressure rather than gases--particularly in light of the flow structures often found on their floors. Therefore, a comparison of the lava tubes to the blisters could help illustrate the changes in tube-related morphology with time.

REFERENCES CITED

Hon, K. and Kauahikaua, J., 1991, The importance of inflation in formation of pahoehoe sheet flows [abs.], EOS, v. 72, no. 44, p. 557.

Hon, K., Kauahikaua, J., and McKay, K., 1992 in preparation, Emplacement and inflation of pahoehoe sheet flows - observations and measurements of active Hawaiian lava flows.

Jackson, D.B., Hort, M.K., Hon, K., and Kauahikaua, J., 1987, Detection and mapping of active lava flows using the VLF induction techniques, Kilauea Volcano, Hawaii [abs.]: EOS, v. 68, no. 44, p. 1543.

Jackson, D.B., Kauahikaua, J., Hon, K., and Heliker, C., 1988, Rate and variation of magma supply to the active lava lake on the middle east rift zone of Kilauea volcano, Hawaii [abs.], GSA Annual Meeting

Kauahikaua, J., Moulds, T., and Hon, K., 1990, Observations of lava tube formation in Kalapana, Hawai`i [abs.], EOS, v. 71, p. 1711.

Tilling, R.I., Christiansen, R.L., Duffield, W.A., Endo, E.T., Holcomb, R.T., Koyanagi, R.Y., Peterson, D.W., and Unger, J.D., 1987, The 1972-1974 Mauna Ulu eruption, Kilauea volcano: an example of a quasi-steady-state magma transfer, USGS Professional Paper 1350, p. 405-469.

Walker, G.P.L., 1989, Spongy pahoehoe in Hawaii : a study of vesicle-distribution patterns in basalt and their significance, Bulletin of Volcanology, v. 51, p. 199-209.

FIGURE CAPTIONS

Figure 1. Sketch map showing area covered by the 1969-1971 Mauna Ulu eruption (shaded), the 1972-74 Mauna Ulu eruption (outlined by solid line), and the outcrop distribution over the present Chain of Craters Road (modified from Tilling and others, 1987).

Figure 2. Schematic sketches of A) typical lava tube with zones of vesicle concentration and B) "gas blister" with concentric vesiculation pattern and rough texture of inner surface.

Figure 3. a) histogram showing the distribution of the aspect ratio values, and b) histogram showing the distribution of the logarithm of the aspect ratio values. The log-transformed values have a more symmetric distribution (lower skew) than the untransformed values.

Figure 4. Plot of height versus width of the tube interiors. Almost all of the points fall above a line (shown) with a slope of one. The height-to-width, or aspect, ratios will therefore be less than one.

Figure 5. Plot of floor thickness versus roof thickness. The majority of points fall above the line shown (slope = 1), indicating that the majority of tubes have floors thicker than their roofs (including any infilling in the floor measurement).

Figure 6. Aspect ratios versus interior cross-sectional area.

Figure 7. Relation of slope to A) size and B) aspect ratio of the tubes. Note the distinct lack of correlations.

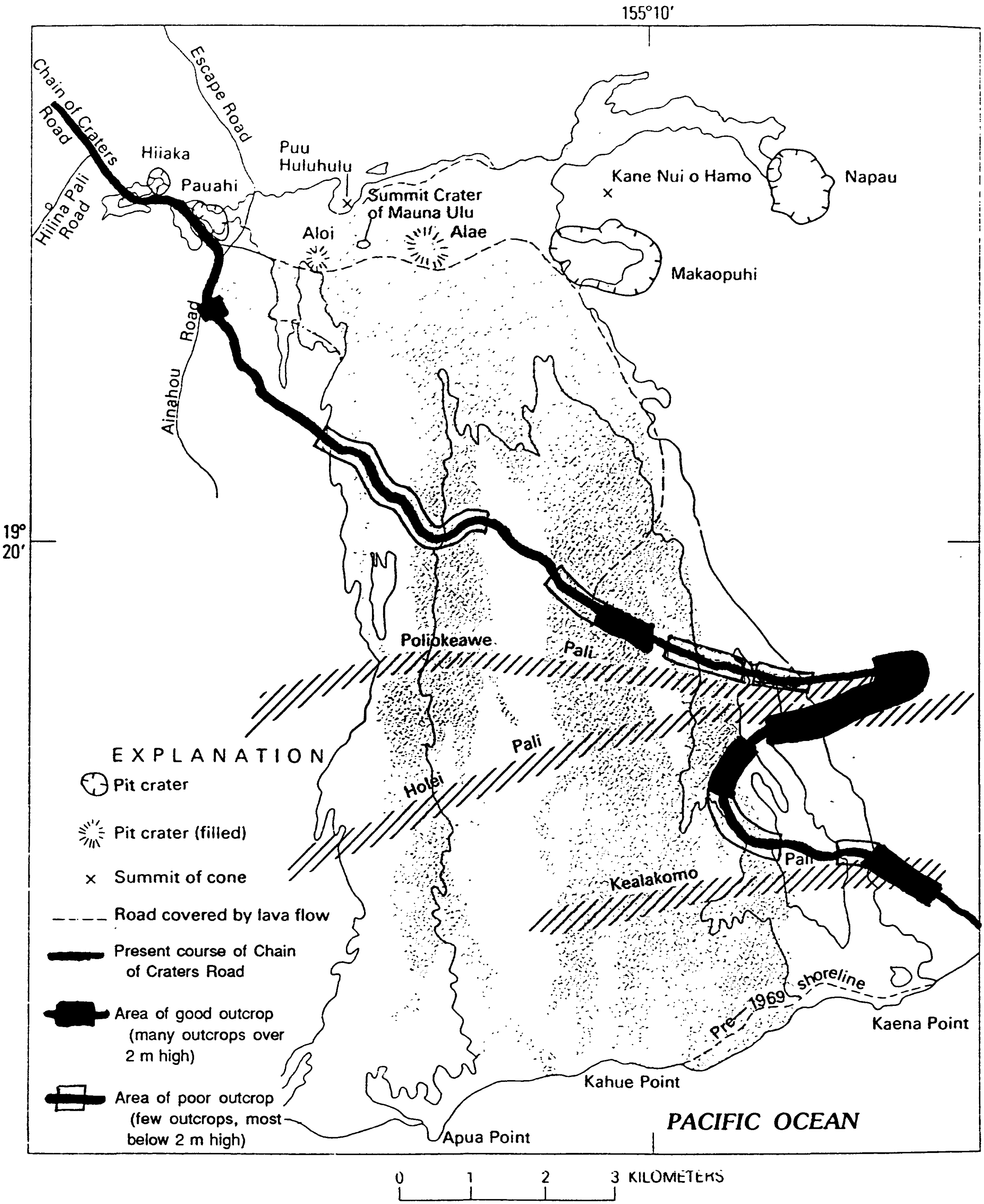

155°10′
19°
20′
Chain of Craters Road
Escape Road
Hiiaka
Pauahi
Hilina Pali Road
Puu Huluhulu
Summit Crater of Mauna Ulu
Kane Nui o Hamo
Napau
Aloi
Alae
Makaopuhi
Ainahou Road
Poliokeawe
Pali
Holei
Pali
Kealakomo
Pali
Pre-1969 shoreline
Kaena Point
Kahue Point
Apua Point
PACIFIC OCEAN
EXPLANATION
Pit crater
Pit crater (filled)
Summit of cone
Road covered by lava flow
Present course of Chain of Craters Road
Area of good outcrop (many outcrops over 2 m high)
Area of poor outcrop (few outcrops, most below 2 m high)
0 1 2 3 KILOMETERS

Figure 1

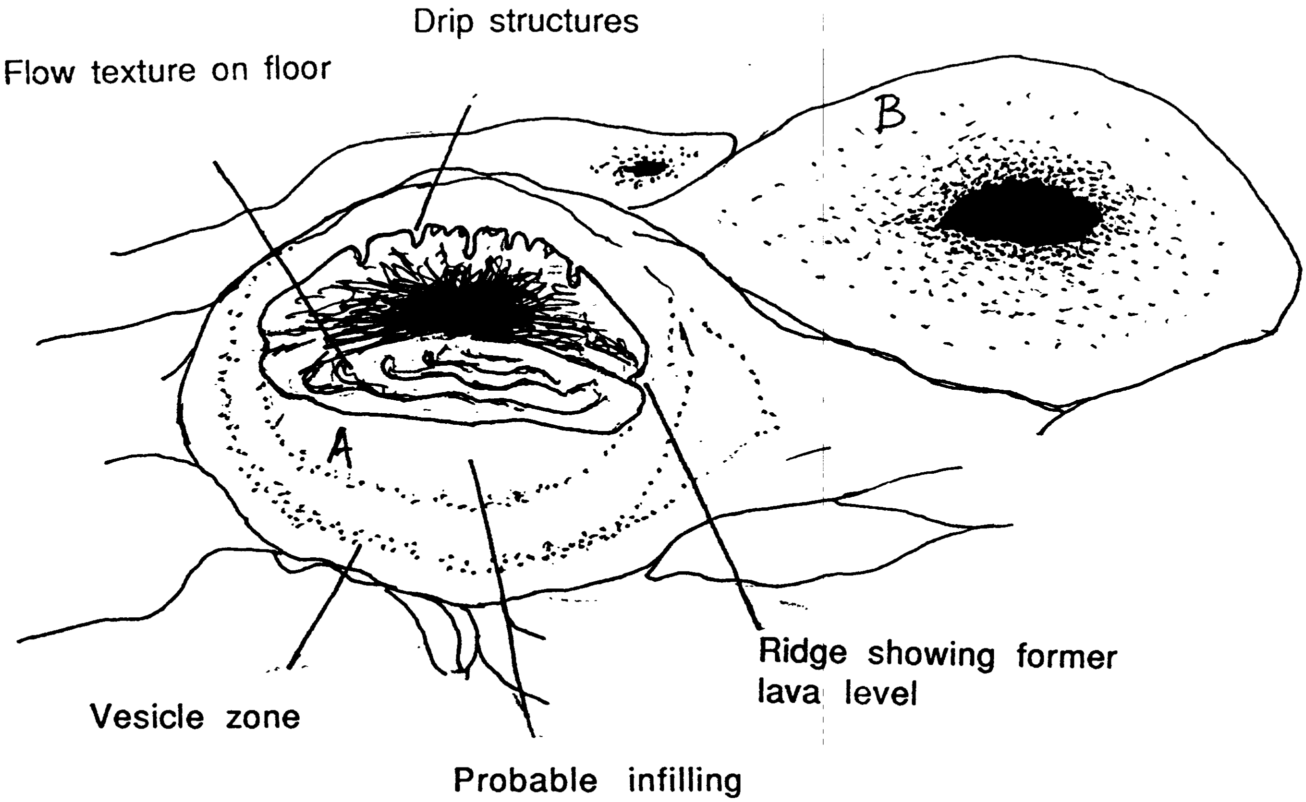
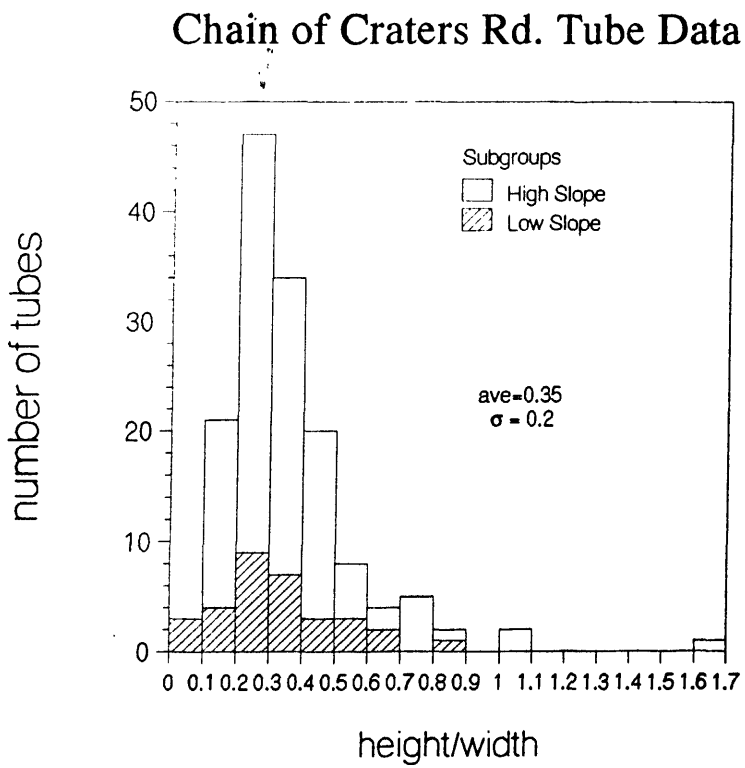

Drip structures
Flow texture on floor
B
A
Ridge showing former lava level
Vesicle zone
Probable infilling

Figure 2


Chain of Craters Rd. Tube Data
number of tubes
height/width
Subgroups
High Slope
Low Slope
ave=0.35
σ = 0.2
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7
0 10 20 30 40 50

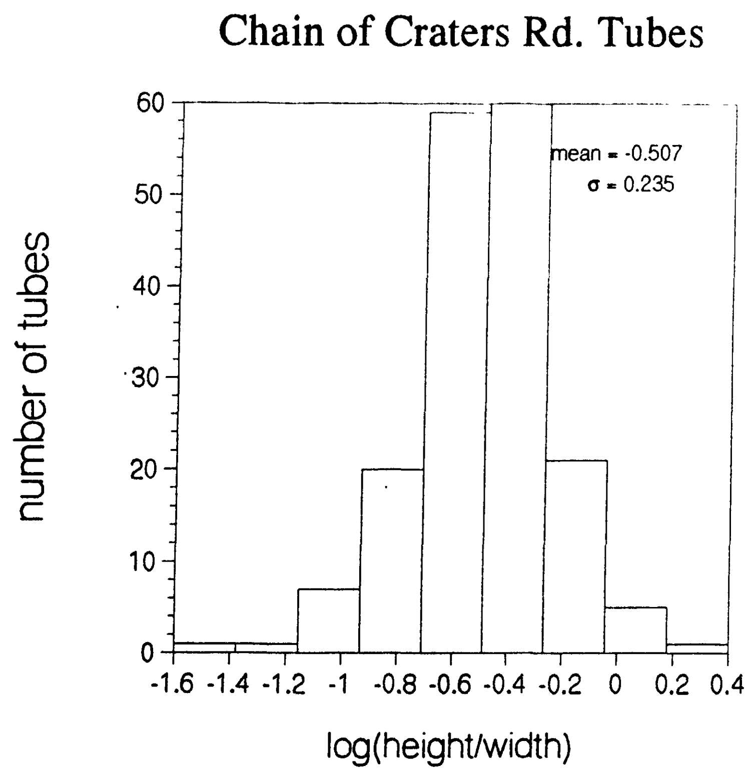

Chain of Craters Rd. Tubes
number of tubes
log(height/width)
mean = -0.507
σ = 0.235
-1.6 -1.4 -1.2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4
0 10 20 30 40 50 60

Figure 3

Height vs Width

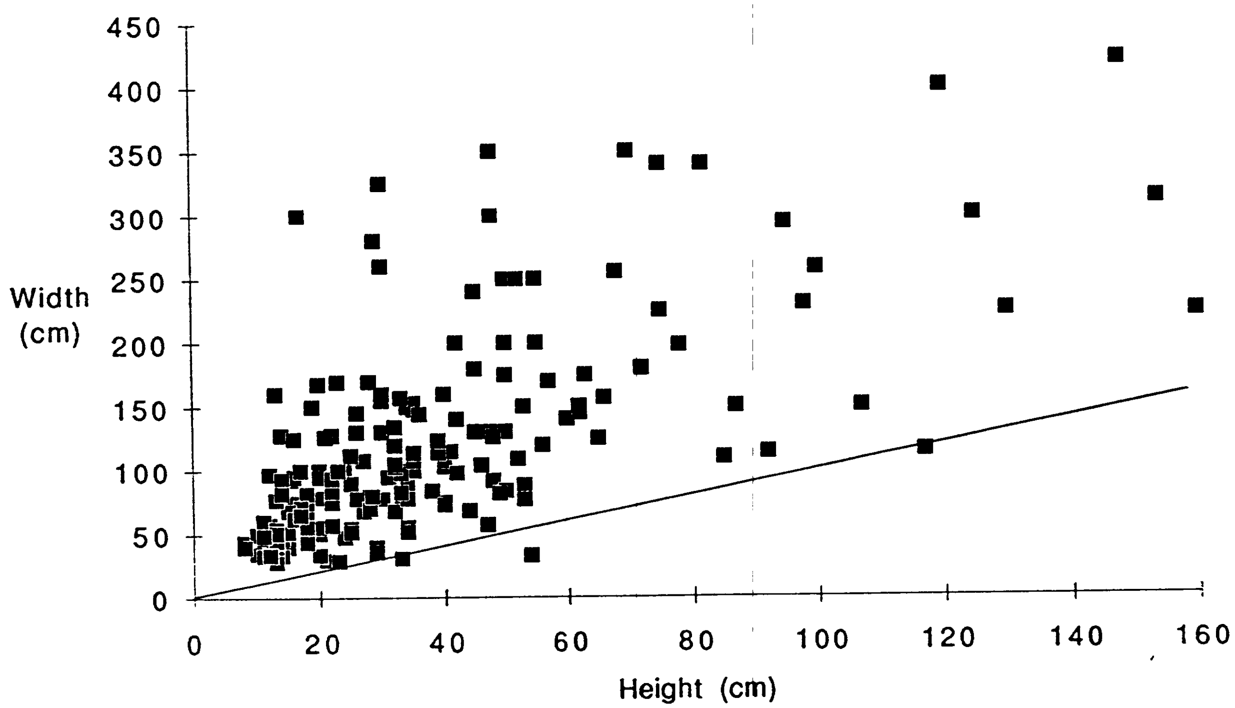


Figure 4

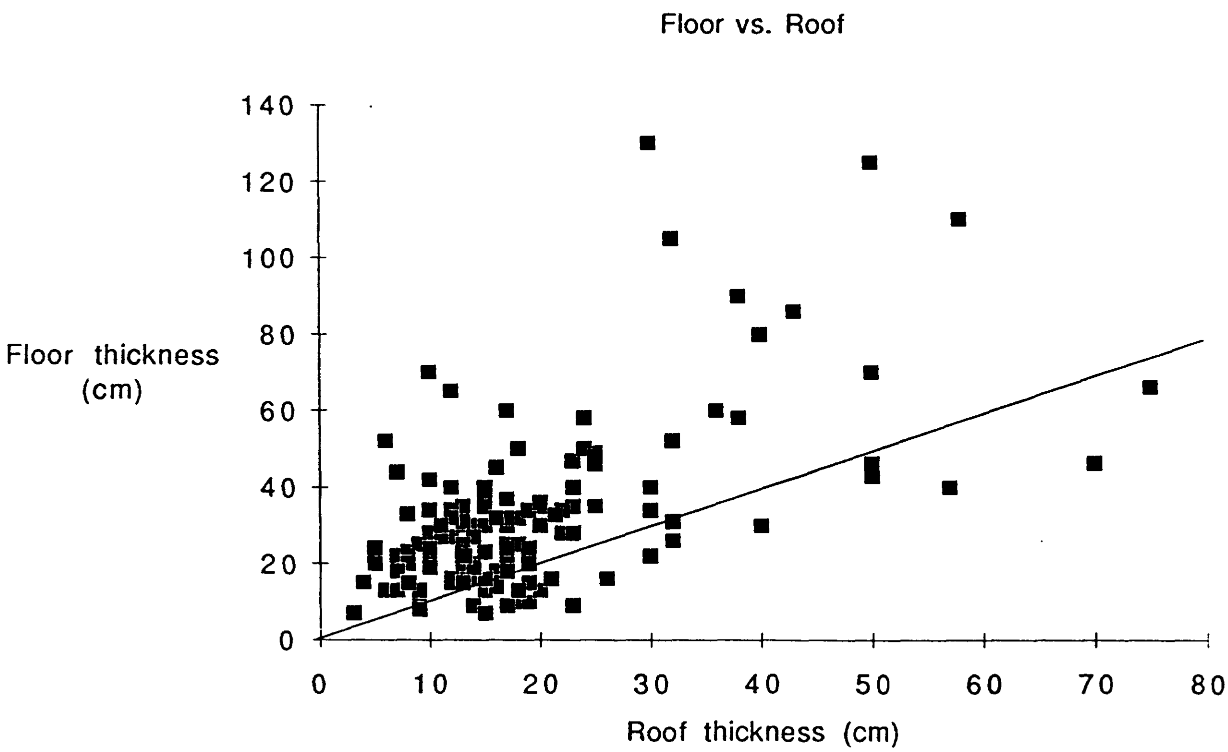
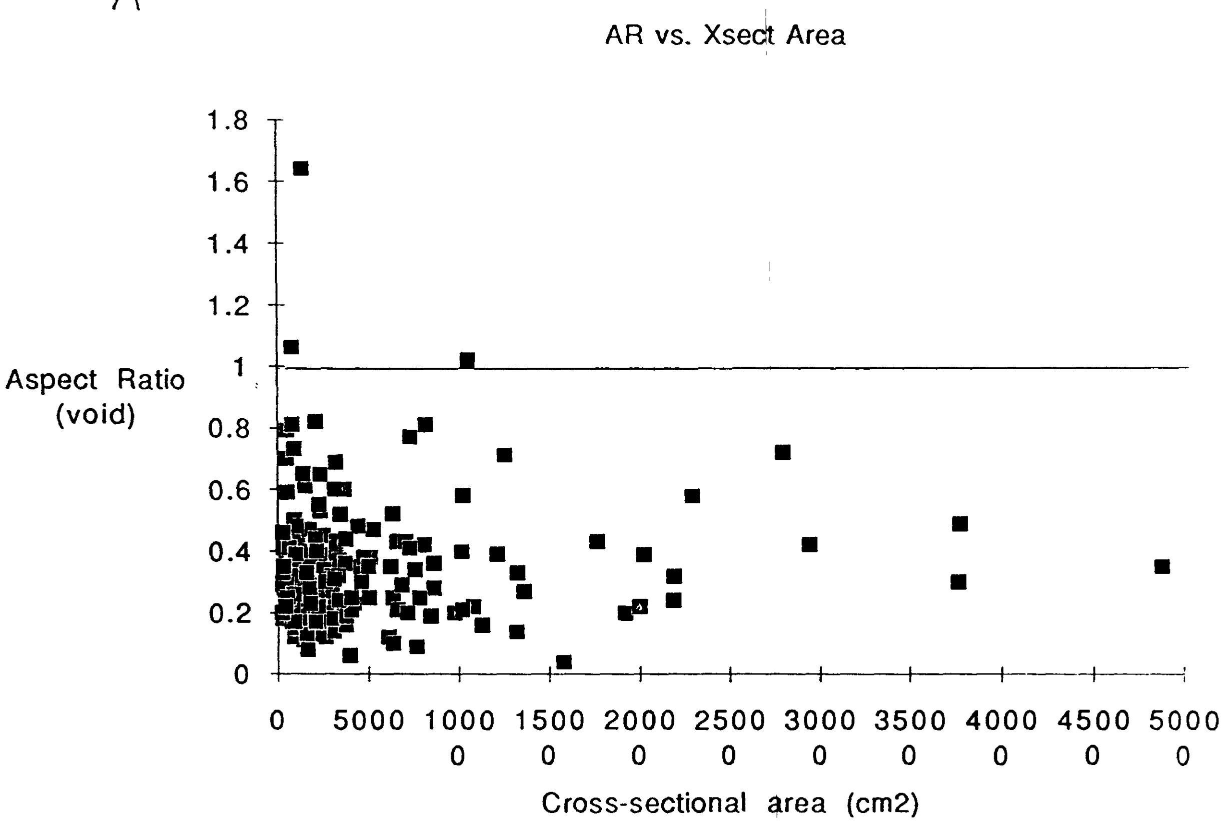

Floor vs. Roof
Floor thickness (cm)
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
Roof thickness (cm)

Figure 5

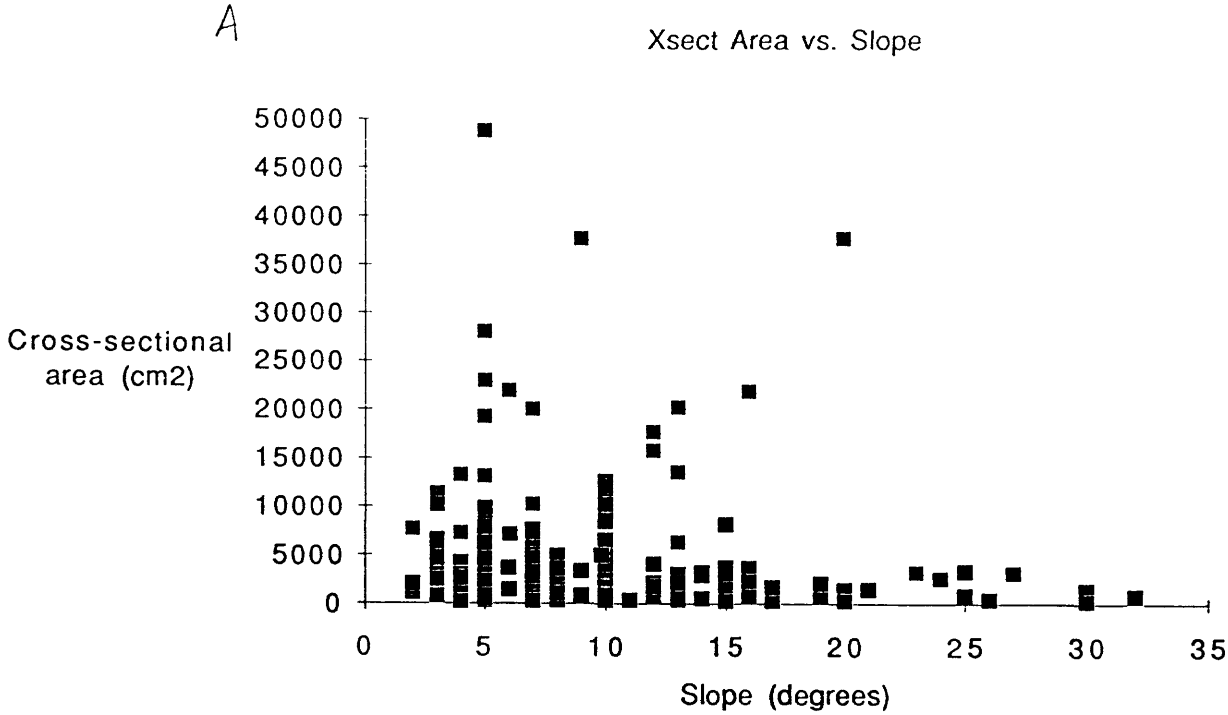
A



AR vs. Xsect Area
Aspect Ratio
(void)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5000
1000
0
1500
0
2000
0
2500
0
3000
0
3500
0
4000
0
4500
0
5000
0
Cross-sectional area (cm2)

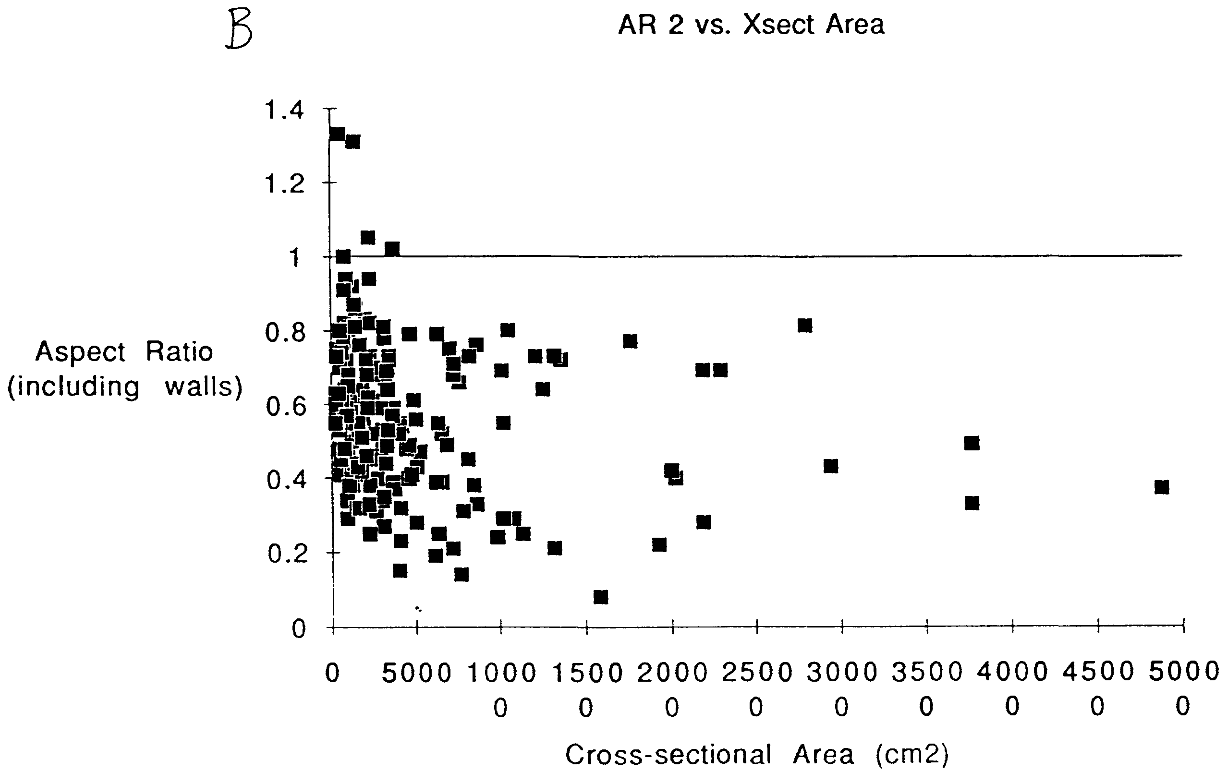
Figure 6

A



Xsect Area vs. Slope
Cross-sectional area (cm2)
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
5
10
15
20
25
30
35
Slope (degrees)

B



AR 2 vs. Xsect Area
Aspect Ratio (including walls)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5000
1000 0
1500 0
2000 0
2500 0
3000 0
3500 0
4000 0
4500 0
5000 0
Cross-sectional Area (cm2)

Figure 7