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VESICLE DISTRIBUTION IN GLACIOVOLCANIC PILLOW LAVA FROM UNDIRHLÍÐAR, SOUTHWEST ICELAND

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INTRODUCTION

This paper analyzes the distribution and emplacement mechanisms of vesicles in pillow lavas found in Undirhlíðar Quarry. These pillows are the only lasting record of a preexisting englacial lake formed during a subglacial eruption, so understanding the details of their vesicles may provide new insights into the timing and nature of their emplacement. Because most pillow lavas are inaccessible, being able to analyze pillow lava using visible characteristics like vesicles without requiring samples would greatly facilitate research.

PILLOW LAVA MORPHOLOGY

Pillow lavas form an interconnected tangle of subaqueous tubes that move sporadically downslope (Macdonald, 1953; Jones, 1967; Moore, 1975; Walker, 1992; Sánchez et al., 2012). Direct observation by Sánchez et al. (2012) and lab experiments by Gregg and Fink (2000) indicate that pillow lavas are emplaced at relatively low flow rates (< 1 m^3/s), on low slopes, and with a relatively high cooling rate.

Magma is immediately quenched as it hits water, forming a glassy rind. As a pillow cools, it forms a crust. Depending on the crust thickness, pillows grow by stretching or by cracking and expanding (Moore, 1975). Walker (1992) determined that pillow growth is controlled by viscosity and that smaller pillows grow more rapidly. Burial by successive pillows and the flow of fresh lava decreases the cooling rate, while cracks allow water into the pillow body, causing rapid cooling (Moore, 1975; Gregg and Fink, 2000; Höskuldsson et al., 2006).

VESICLE DISTRIBUTION

Previous studies of vesicle distribution in pillow lavas have identified concentric vesicle patterns, radial pipe vesicles (Sánchez et al., 2012), and distinct vesiculated cores (Höskuldsson et al., 2006). Jones (1969) reported vesicle size decrease in pillows at depth. Vesicle morphology is controlled by dissolution, expansion, ripening, coalescence, flow, and viscosity (Cashman et al., 1994; Gaonac'h et al., 1996; Herd and Pinkerton, 1996; Manga, 1996). Vesicles are usually distributed heterogeneously and have variable volumes with ratios up to 10^7 (Gaonac'h et al., 1996). Expansion and diffusion dominate small bubble growth, but coalescence prevails as they increase in size (Gaonac'h et al., 1996). In lava tubes, which may resemble pillow feeding tubes, large vesicles escape via passive rise down tube. Meanwhile, small vesicles develop, indicating continuous volatile exsolution (Cashman et al., 1996).

METHODS

Field Work

Measurements and detailed observations of pillow lavas were made of 47 pillows at the central, opposite central, south, upper north, and mid north walls. A system to categorize pillow vesicle patterns was developed based on the presence of a vesiculated core, vesicles in the body, and a hollow pocket (Fig. 1a). Cores are distinguished by a different concentration and/or average size of vesicles from the pillow body. The presence of vesicle rings was rated in each pillow on a scale from zero (no rings) to three (well-defined

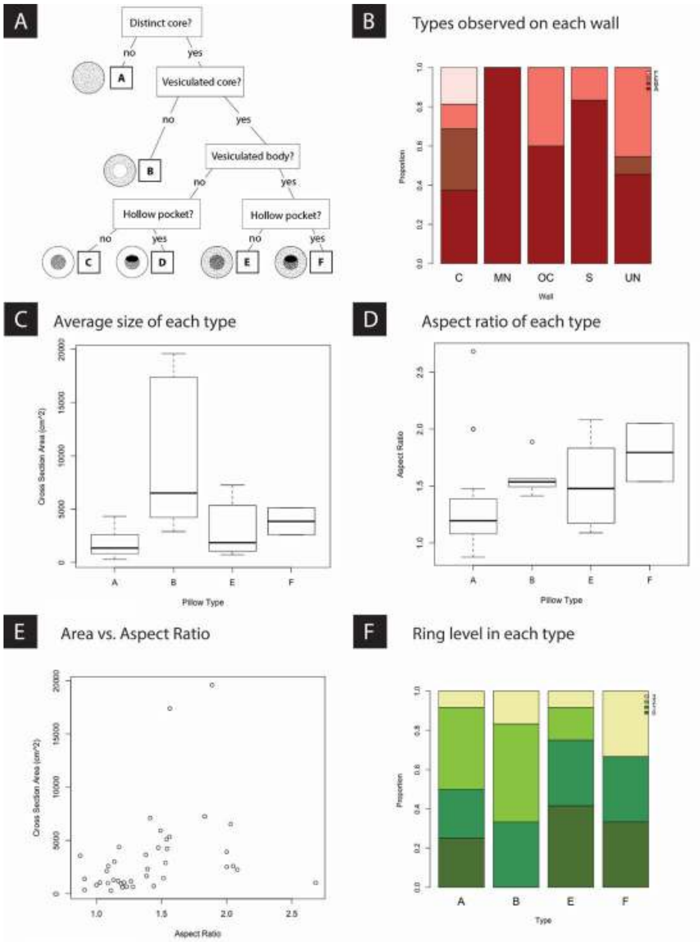


Figure 1. Method (A) and results (B-D) of pillow characterizations. Approximate cross sectional area, calculated assuming pillows are perfect upright ellipses, and aspect ratio are plotted by type (E-F).

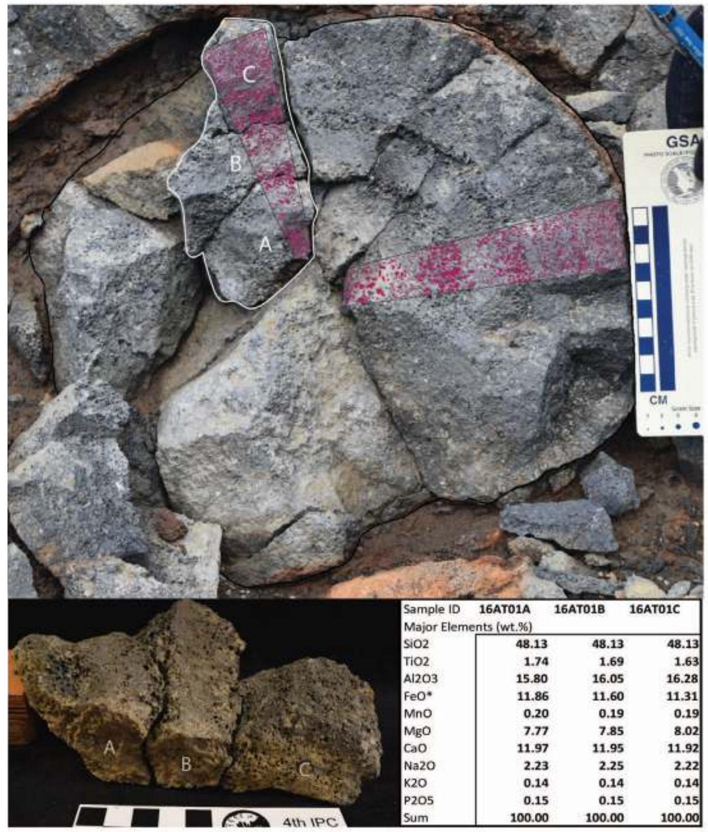
rings). Pillows were recorded in an attempt to account for every recognizable type on all five quarry walls.

Image Processing

I traced vesicles from a photograph of pillow P11UN, which has well defined rings, using Adobe Illustrator (Fig. 2). Image resolution limited minimum vesicle size. Using ImageJ, I analyzed average vesicle size, density, aspect ratio, and circularity in 0.5 cm segments of the traces.

Hand Samples

Sample 16AT01 spanned pillow P11UN from center to edge (Fig. 2). To look for compositional variations within the pillow, I prepared glass beads from fresh whole-rock powder to be analyzed by XRF at the



Sample ID	16AT01A	16AT01B	16AT01C
Major Elements (wt.%)			
SiO2	48.13	48.13	48.13
TiO2	1.74	1.69	1.63
Al2O3	15.80	16.05	16.28
FeO*	11.86	11.60	11.31
MnO	0.20	0.19	0.19
MgO	7.77	7.85	8.02
CaO	11.97	11.95	11.92
Na2O	2.23	2.25	2.22
K2O	0.14	0.14	0.14
P2O5	0.15	0.15	0.15
Sum	100.00	100.00	100.00

Figure 2. Vesicle trace of two transects from pillow P11UN, and samples 16AT01 A, B, and C. Major element geochemistry was analyzed for the innermost portion of A, B, and the outermost portion of C.

College of Wooster for major element geochemistry. XRF sample preparation and analysis followed the methods of Pollock et al. (2014).

I analyzed a thin section transect of sample 16AT01 using Carleton College's Hitachi S-3000N Scanning Electron Microscope (SEM) equipped with an Oxford INCA microanalysis system. I operated the SEM in variable pressure mode at 20 Pa with a voltage of 20 kV, beam current between 95 and 106 uA, and working distance of 15 mm. I analyzed mineral chemistry of microlites at 1000x magnification and captured images at 120x at eight sites across the transect.

Vertical Distribution Model

I created a one-dimensional model to calculate the vertical distribution of vesicles within a stagnant pillow lava. The model breaks the vertical pillow transect into 20 stacked blocks that each have a unique temperature, viscosity, and terminal rise velocity. The simulation begins with 21 evenly spaced vesicles. The vertical position of the vesicles, as controlled by gravity, is calculated at every time step.

I assumed the initial emplacement temperature across the pillow to be the liquidus temperature. The MELTS applet, created by Ghiorso and Sack (1995) and Asimow and Ghiorso (1998), used the major element composition of sample 16AT01A to determine the liquidus temperature at an oxygen fugacity set to the QFM+ buffer and a pressure of 2000 bars to simulate the source magma chamber depth. Temperature in the following time steps is defined by a cooling model written by Ben Edwards using equations from Crank (1975) for diffusion in a cylinder using Bessel Functions (Ben Edwards, personal communication).

At every time step, the viscosity of each block is calculated using the methods of Giordano et al. (2008), based on major element geochemistry and temperature. The viscosity cutoff was determined using MELTS results for sample 16AT01A that include percent liquid mass corresponding to viscosity. According to Marsh (1995), vesicles can no longer move through a magma with more than 55% crystals. Thus, the temperature cutoff for the model is considered the temperature at which crystallinity reaches 55%.

The terminal rise velocity of vesicles is calculated in each block using Stoke's Law, which accounts for vesicle size, the density of a vesicle, magma density, and magma viscosity. The vesicle size used is the average size of the vesicles traced for image analysis on pillow P11UN. Magma density was determined from major element geochemistry, pressure, and temperature, using methods of Bottinga and Weill (1970). The pressure value was obtained from a sample of fresh glass collected near 16AT01A. The water content, calculated by Chloe Wallace using FTIR, composition, and the liquidus temperature, was used in a solubility model to calculate an eruption pressure of five bars, which corresponds with an ice thickness of 55.64 m (Wallace, this volume).

The model uses the terminal rise velocity and time step to calculate expected vesicle rise in each block. If the amount of expected rise is greater than the height of the block, the additional rise is calculated with regards to the viscosity of the above block. If a vesicle reaches a block with a temperature less than the temperature cutoff or the top edge of the pillow, it will not rise beyond that boundary.

This model only accounts for vesicle rise due to gravity and viscosity, and assumes that vesicle position was evenly distributed at emplacement. It further assumes that the pillow edge is in constant contact with zero-degree water, and that the lava is stagnant and cools only by conduction.

RESULTS

Pillow Scale Observations

I observed two general trends in vesicle distribution. First, vesicles tend to concentrate in the upper half of pillows, and in some cases, pillows are found to have hollow pockets. Second, vesicle distribution is typically organized concentrically. The largest and most highly concentrated vesicles are generally found in the upper half of the core or vesicle rings. In some less common cases, pillows have dense cores with very small or no vesicles.

Four out of six possible vesicle distribution types were identified in Undirhlíðar Quarry (Fig. 1b). Pillow types C and D, the only types without vesiculated pillow bodies, were not observed anywhere. Pillow types A and E were observed on almost every wall (Fig. 1b). Pillows with hollow pockets (type F) were unique to the central wall, and pillows with non vesiculated cores (type B) were unique to the central and upper north walls.

Plots of pillow area and aspect ratio (Fig. 1c and 1d) reveal that type B pillows are nearly twice as large as the other pillow types. Type A pillows, which do not have distinct cores, are the most circular, and type F, which have hollow pockets, are the least. A plot of aspect ratio vs. area (Fig. 1e) reveals that they are loosely correlated. Figure 1f shows the relationship between ring level and pillow type. Note that type B pillows were always observed to have vesicle rings, and have the most well defined rings.

Image Processing

ImageJ analysis results were plotted to determine which vesicle characteristics define vesicle rings (Fig. 3). There are noticeable peaks in average vesicle size and percent area of vesicles that correspond with the position of vesicle rings. There is a slight peak in average aspect ratio and a low point in average circularity corresponding to the vesicle rings in trace P11UN02, however these peaks are not distinct enough to be confidently attributed to the presence of vesicle rings. There is no distinguishable peak or low point in vesicle density on either transect, so it is not considered to be related to the presence of vesicle rings.

Geochemistry and Thin Sections

XRF geochemistry results of pillow P11UN (Fig. 2) indicate that there is no significant compositional change within the pillow. This confirms that vesicle patterns are not compositionally controlled since the major element concentrations are nearly identical across the pillow, and all plot as basalt on a TAS diagram. SEM Ca and Na components of microlite mineral chemistry and crystal size results varied, but revealed no regular pattern relevant to vesicle rings along the transect.

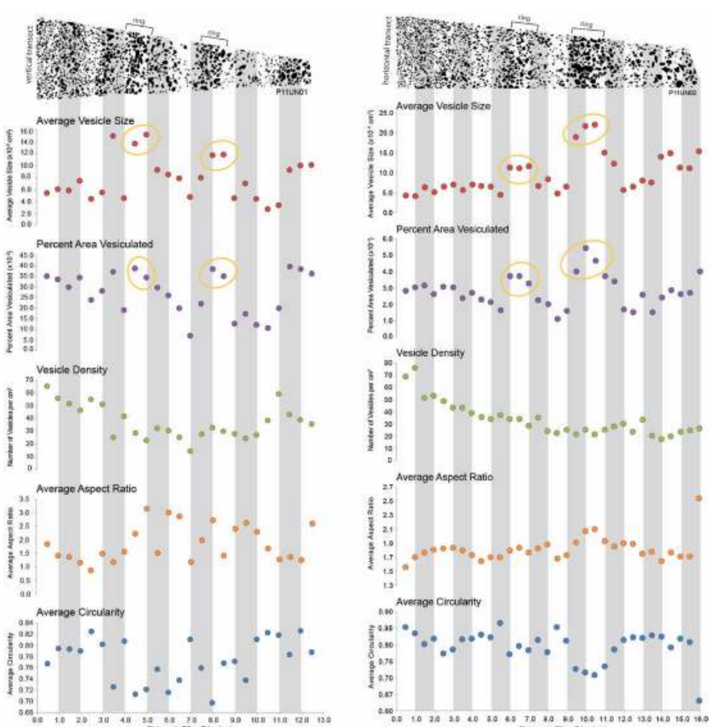


Figure 3. Results from ImageJ analysis of traced transects in half centimeter segments identified by gray and white bars. Peaks that correspond with vesicle rings are circled.

Vertical Distribution Model

The results of the vertical distribution model (Fig. 4) demonstrate how vesicles become concentrated in the top halves of pillows, while a few are still caught in the lower halves. It is first evident, by comparison between the plots of differently sized pillows, that vesicles are more evenly distributed in smaller pillows

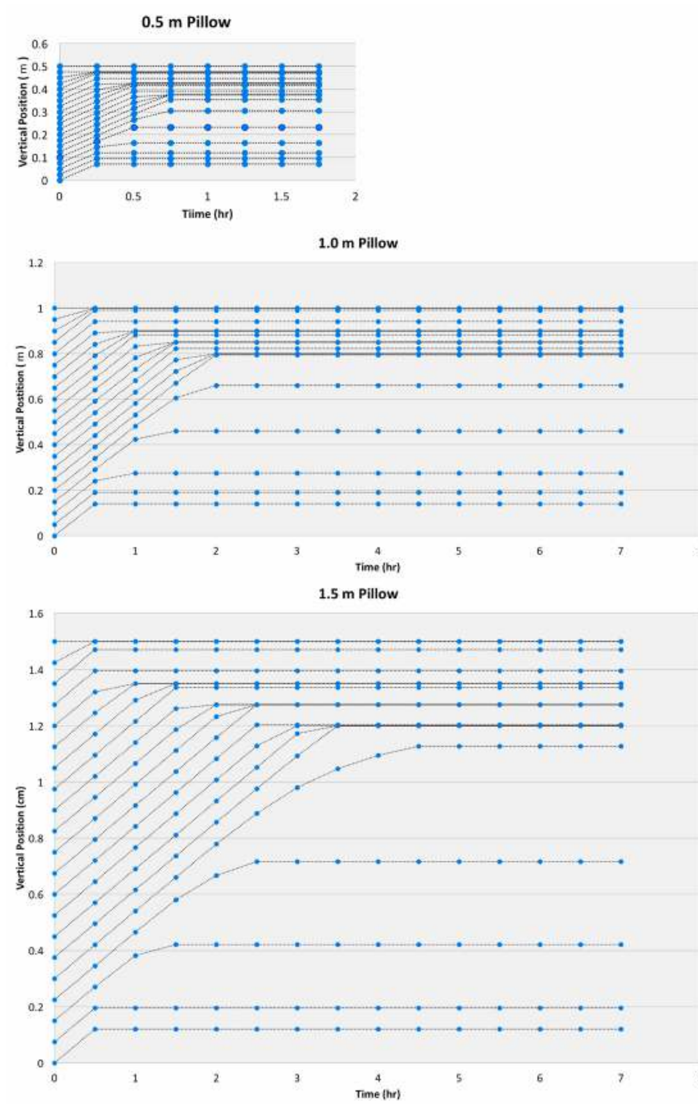


Figure 4. Results of the vertical rise model with variable pillow diameters. Note the smaller time step in the 0.5 m pillow. At time = 0 hours, vesicles are distributed evenly. Over time, vesicles rise while the pillow cools from above and below. The vesicles rise more slowly on the edges where the pillow is cooling, and are locked in place or pool against cooling fronts where the melt becomes impassible at 55% or more crystallinity. For example, it is possible to see where three vesicles pool against a cooling front at 1.25 m between 2.0 to 2.5 hours of cooling in a 1.5 m pillow.

by the time they cool. In the case of a 0.5 m diameter pillow, this takes three quarters of an hour. Conversely, the vesicles of a 1.5 m pillow are more concentrated at the top. This is because fewer vesicles are caught by the cooling front on the bottom edge, and they have 4.5 hours to continue rising before the pillow is cooled to the center.

DISCUSSION

My goal was to understand what controls vesicle distribution, which resulted in a method to infer eruption environment based on recognizable vesicle patterns.

Interpretation of Pillow Types

Höskuldsson et al. (2006) observed that most pillows less than 0.6 m in diameter lack a vesicular core, and Walker (1992) determined that smaller pillows grow by stretching their skin and have smooth surfaces. Type A pillows are relatively small and round, and lack a vesicular core. I propose that type A pillows are the farthest reaching extent of pillow tubes, thus being smaller than their upslope counterparts. Being at the end of a tube would also allow them to cool more quickly, leaving less time for vesicles to rise. This is consistent with the observation that vesicles in type A pillows are relatively evenly dispersed.

The bodies of type B pillows are vesiculated and ringed like many type E and F pillows. Type B pillows are larger on average, indicating that they grew for a longer period of time. Type B pillows were most likely emplaced near the source and cooled slowly because of the flow of lava through their center. They will not have solidified before a later eruption that filled the distinctly nonvesiculated cores with degassed magma containing few vesicles.

Type E pillows are characterized by their highly vesiculated cores. Höskuldsson et al. (2006) proposed that vesiculated cores are a result of extreme changes in pressure. The source of the pressure change might have rapid drainage by jökulhlaups. Sudden depressurization has been known to reactivate eruptions, which results in new pulses of magma and larger vesicles.

The source of type F pillows was probably cut off or diverted, distinguishing them from type B and E pillows. A hollow pocket formed in the wake of the still liquid lava that drained the pillow tube (Moore 1975). The relatively flattened shape of type F pillows indicates that pillows were still soft when drained, causing them to slump as it cooled.

Rings

Concentric vesicles rings were a prominent feature in all pillow types. Flow through pillow tubes may organize vesicles in cylinders similar to the way they form sheets in lava flows (Manga, 1996), so that they

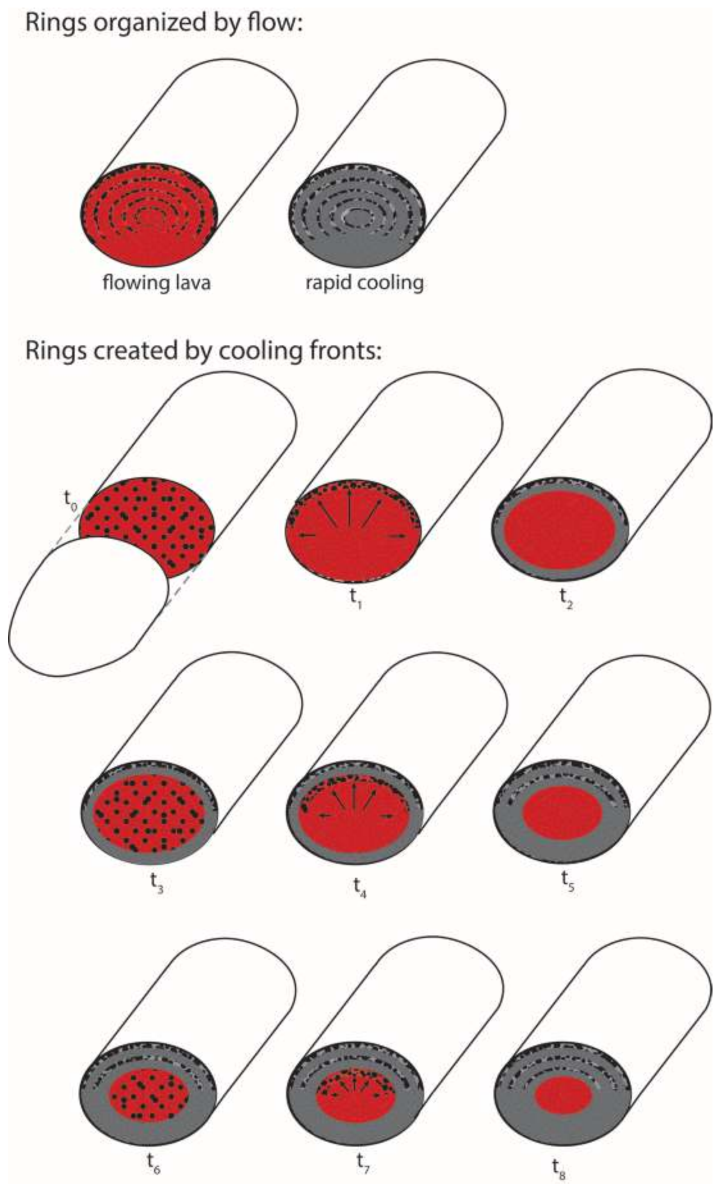


Figure 5. Two possible mechanisms for vesicle ring formation. Rings will be more concentrated in the upper half of pillows.

look like concentric rings in cross section (Fig. 5). In this scenario, the pillow would have to cool rapidly after emplacement before the vesicles rise out of their concentric position. This explanation does not account for pillow formation without rings or the fact that type B pillows always have rings, despite being large and slow cooling.

Another possible interpretation is that each vesicle ring represents a pulse of fresh magma. At t_0 (Fig. 5), a new pillow tube is emplaced with evenly distributed vesicles. A glassy rim is immediately quenched. At t_1, vesicles move to the edge of the pillow. By t_2, a few centimeters of crust have cooled, trapping the highest concentration of vesicles where they have pooled on outside edge. At t_3, a new pulse of magma is fed through the tube. Vesicles pool against the new cooling front in t_4, where they are locked in place by cooling in t_5. This process can be repeated as many times as necessary to match the observed number of rings. The inward growth also accommodates the formation of any type of core, like those observed in pillow types B and F.

Vertical Distribution Model

The proposed setting of type A pillows could be most easily modeled using the vertical distribution model. The observed distribution most closely matches the results that the simulation produced for small pillows like type A. I was able to model how vesicles collect at the pillow edge, and further adjustments could be made to simulate new pulses of magma and rings formed by vesicles that pool against cooled margins.

CONCLUSIONS

My investigation revealed that vesicle distribution is controlled by gravity, viscosity, and pressure, but is not influenced by magma composition. Vesicle rings and cores are characterized by an increase in vesicle size and number. They may represent different events, like magma pulses or sudden changes of pressure in the surrounding environment. The type of vesicle distribution in a pillow cross section may be used to infer proximity to the source, the rate at which the pillow cooled, and eruption events during pillow emplacement. Future studies that systematically characterize distribution type at different elevations or distances from the source could be used to support these findings.

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