Analysis of Bubble Sizes in Vesicular Basalt

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ABSTRACT

Vertical variation in basalt vesicle size and abundance has traditionally been utilized as a relative-age indicator in deformed volcanic terrains. However, there is more to be learned from vesicles than simply which way is up. Recent study of vesicle size-frequency distributions has resulted in quantification of rates of volatile exsolution in pre-eruption magmas, flow motion and cooling processes, as well as the elevation of lava emplacement.

Through analysis of vesicle size-frequency distributions from a series of slabs cut from a single basalt hand-sample, students are introduced to simple rock preparation techniques and subsequent numerical analysis. Additionally, comparison of size-frequencies between sequential slabs allows for introduction of these techniques and the mathematics of bubble growth in fluids.

From our example analysis, it was determined that vertical variation in the size-frequency distribution of basalt vesicles over short distances implies multiple processes of bubble growth. In our sample, bubble enlargement occurred largely through coalescence during buoyant ascent. Systematic vertical variation in negative exponential distributions of vesicle sizes indicates that initial coalescence of bubbles is followed by minor inflation and selective combination of only the largest bubbles as lava cools.

Keywords: Miscellaneous and mathematical geology; petrology – igneous

Introduction

The growth of bubbles of volatile gasses within basaltic lava is controlled by a complex set of factors, including dissolved gas content, flow thickness, and atmospheric pressure at the site of emplacement. Through the procedure illustrated below, students are introduced to quantitative analysis and subsequent interpretation of the results in terms of interrelated processes of bubble growth.

Analyses of size-frequency distributions of vesicles in basalt have resulted in quantification of rates of volatile exsolution (Mangan and others, 1993), flow motion and cooling (Aubele and others, 1988; Cashman and others, 1994), as well as elevation of lava emplacement (Sahagian and Maus, 1994). Additionally, vertical variation in vesicle size and abundance are commonly utilized as relative-age indicators in deformed volcanic terrains (Davis, 1984). In this paper, we describe the results of a detailed, yet elementary, analysis of vertical variation of vesicle size-frequency distributions over a scale of several centimeters, as well as the implications for bubble growth derived from those observations.

Procedure

To begin our analyses we chose a large (~16 cm diameter) hand-sample of vesicular basalt from our departmental rock and mineral collection. Care was taken to select a sample which exhibited visually pronounced vertical variation in vesicularity, both with regard to size and abundance of vesicles. The sample was then cut into a series of thin (1-3 cm) slabs, parallel to the horizontal at the time of extrusion, using a standard oil-bath rock saw. Each slab was polished on a lap wheel to remove saw marks, and then stained with a black permanent felt-tip marker. Acetate peels were prepared for each slab using standard techniques (Muller, 1967). The ink from the slab was taken up by the acetate, allowing for a sharp contrast between the vesicles and the basalt matrix (Figure 1a and b). The peels were then digitally scanned at a resolution of 300 dpi using a 16-tone gray-scale desktop scanner. Measurement of vesicle cross-sectional area was done by image-analysis software on pseudo-color mappings of these grey-scale images. False-color images of the grey-scale scans were used to highlight the contrast between bubble and basalt as well as to recognize regions where ink had bled into vesicle openings. Individual vesicles with cross-sectional areas as small as 10^-3 cm^2 were resolved, with standard deviation of replicate area measurements maintained at less than four percent of the modal value. Vesicle abundance was then normalized to the surface area of each particular slab (divide vesicle frequency by total sample area to produce vesicle frequency per cm^2) to facilitate comparison of size-frequencies throughout the hand sample. For laboratories lacking scanners and advanced software, photocopy enlargements (150-200%) of the stained peels could be used in combination with a simple manual planimeter to measure vesicle area with only a slight reduction in precision and resolution.

Analysis of Data

Measurements made on two-dimensional representations of three-dimensional objects are subject to several types of errors. First, many vesicles are not perfectly spherical; thus, for comparison, all measurements must be converted to equivalent spherical geometries. In the case of typical vesicular-basalt samples, the deviation from sphericity is minor, and thus a spherical geometry is a reasonable approximation. Second, the probability of intersecting a vesicle of any given volume with a randomly oriented plane is proportional to
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Figure 1. Photographs of basalt slab (A) and acetate peel (B) scale is in centimeters.

the sphere's volume (Mangan and others, 1993); thus small vesicles might be under-represented relative to larger ones. However, if the plane of the slab is cut perpendicular to the direction of bubble migration, vesicles in any sample will follow a uniform random spatial distribution with all sizes being fairly represented. This two-dimensional random distribution is then taken as an accurate measure of three-dimensional vesicularity over the scale of a single slab. Third, any intersection of a sphere with a plane resulting in a non-symmetrical bisection produces an under-representation of cross-sectional area (Cheng and Lemlich, 1983; Cashman and Marsh, 1988; Mangan and others, 1993). Numerical simulation indicates that vesicle volumes calculated from erroneous cross sections average 2/3 of true volume; thus, an error correction factor can be applied to calculated volumes. However, since this is a linear factor, it does not affect the form of the size-frequency distribution, only the absolute values of individual measurements and, as such, has not been applied in this study.

These analytical concerns serve as a useful starting point for a discussion of error analysis, as well as for consideration of alternative analytical techniques.

How else could one measure vesicle volumes? Possibilities include filling holes with some material and dissolving the rock away or cutting very thin serial slices to determine the vertical change in shape of each vesicle. Students should consider how these other procedures would work, and what problems and errors would be associated with each. Throughout the remainder of this study, however, interpretation of vesicle size-frequencies will be made with respect to raw two-dimensional analysis of bubble area without correction for those errors discussed above.

Observations and Interpretations

Our experimental example involved analyzing three slabs cut from a single hand sample of basalt. In all slabs, vesicles were found to exhibit exponentially decreasing abundance with linearly increasing size (Figure 2). The relative abundance of small to large vesicles varied systematically throughout the hand sample, with small vesicles being more abundant lower in the sample and larger vesicles more abundant near the top (Figure 2, Table 1). Such variation is in keeping with expectations of bubble coalescence and inflation near the tops of flows. However, in this case, change in the form of observed vesicle size-frequency distributions over small vertical distances provides insight into the specific mechanisms of bubble growth.
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Figure 2. Plots of area normalized cumulative frequency distribution of vesicles from samples B8, T4, and T1 versus their equivalent spherical radius. Note the progressive decrease in the slope of the regressions from sample B8 through T1, as well as the reduction in the y-intercept value from B8 to T4.

Table 1 (left). Summary of quantitative analysis of basalt vesicle size-frequencies. Vertical position refers to position of slab relative to the base of the sample, in centimeters, while area is the area of the total sample in square centimeters. Regression and correlation data refer to standard linear regression of vesicle size-frequency distribution in semi-log space, see Figure 2. Maximum bubble density is the estimated total density of bubbles per square centimeter as derived from the y-intercept of the regression line. Note that in the case of sample B8 regression data indicate a large underestimation of the total number of small vesicles present, a likely indication that many very small vesicles were not measured with this technique.
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Figure 3. Illustrations of progressive changes in the size-frequency distributions of vesicles within basalt samples. A – Transition from a high bubble density/small bubble-rich distribution to a lower density/large bubble-enriched distribution occurs via coalescence of small bubbles to form larger ones and is illustrated by a change in slope and intercept. B – Change in slope of bubble distribution with little change in bubble density is consistent with hydrostatic inflation of bubbles.

Bubble coalescence will result in a decrease in the abundance of small vesicles relative to large ones, producing a decrease in the slope of the size-frequency relationship, as well as a decrease in the total abundance of bubbles per unit area (Figure 3a). Conversely, bubble inflation due to decreasing hydrostatic pressure results in a decrease in the slope of the size-frequency relationship but no net change in bubble abundance (Figure 3b). That is, coalescence changes the slope and the intercept of the size-frequency relationship while inflation only changes the slope.

If large numbers of bubble areas are calculated, computation of regression data is only practicable with the use of statistical software associated with spread-sheet-type applications. However, reasonably good fits can be obtained by simple best-fitting lines by eye. The amount of effort an instructor wishes to expend on computation of slopes and intercepts largely depends on the nature of the class conducting the experiment.

From the base to the center of the hand-sample there is a pronounced decrease in the slope of the vesicle size-frequency relationship, as well as a decrease in the total abundance of bubbles per unit area (Figure 2, Table 1). The form of the exponential size-frequency relationship is used to extrapolate the maximum abundance of vesicles per unit area. Bubble density at the base of the sample is calculated to be 12 vesicles/cm², whereas, the middle of the sample has a density of only 6 vesicles/cm². This two-fold decrease in vesicle density is a reflection of the coalescence of small bubbles to form larger ones. Although volumetric inflation must have been operative over this change in vertical position, the observed vesicle size-frequency relationships indicate that the principle process of bubble growth was coalescence. It should be noted that the slight deviation from ideal exponential bubble size-frequency observed in sample B8 is due to a slight under representation of the smallest vesicles, possibly due to an inability to resolve very small vesicles with this technique. Thus, sample B8 has a size-frequency distribution somewhat between a pure negative exponential and a skewed normal distribution.

From the middle to the top of the sample, a different pattern of bubble growth is evidenced by near-constant bubble density (6 to 5.5 vesicles/cm²) with continued decrease in the slope of the size-frequency relationship (Figure 2, Table 1). The nature of this change is similar to that expected for volumetric inflation of bubbles under decreasing hydrostatic pressure. However, a change in slope, such as that observed between the middle and upper slab, would reflect an expansion of individual bubble volume by a factor of 1.56. Such a predicted change is inconsistent with hydrostatic modeling of the sample in question (Shafer and Zare, 1991; Sahagian and Maus, 1994). Inflation of the bubble population by a factor of 1.56 would require a change in vertical position of 2.17 m within a flow of basaltic lava of density 2.63 g/cm³ (Ehlers and Blatt, 1982) at standard atmospheric pressure. This is far too large given that the slabs in question were separated vertically by only 3 cm. Hydrostatic inflation over this small distance would result in negligible change in the form of the size-frequency relationship. Thus, a secondary explanation is required for the origin of the change in slope of the negative exponential relationship.

The nature of the increase in relative abundance of large vesicles at the top of the sample is inconsistent with both processes of widespread bubble coalescence and hydrostatically driven bubble inflation. Therefore, the most likely explanation is that of selective combination of only the largest bubbles. As a newly emplaced lava cools, viscosity near the base and top of the flow increases rapidly (Walker, 1989). This serves to retard further bubble migration and induce selective combination.

of only the largest bubbles which are still able to migrate under the increasingly viscous conditions. Indeed, observation of the top of the hand-sample clearly indicates that the largest bubbles are, in fact, composites of two or more bubbles which have not fully achieved sphericity. This process will result in a very small reduction in the average abundance of vesicles while serving to enlarge the largest bubbles, thereby decreasing the slope of the size-frequency distribution while little altering the total vesicle abundance. If continued for a significant period of time, the size-frequency distribution might develop two distinct populations, as indicated by the formation of an inflection point within the distribution (Mangan and others, 1993). However, in this study, the small degree of coalescence has served to only alter the slope of the distribution.

Conclusions
Detailed analysis of vertical changes in vesicle size-frequency distributions over small distances serves to illustrate the importance of simple rock-preparation techniques, analytical and mathematical techniques, and the relative importance of various processes of bubble growth within basaltic lava. From our experimental example, it is possible to conclude that, although volumetric inflation driven by changing hydrostatic pressure may be a significant component at the meter scale, it has essentially no effect on change in bubble populations at the centimeter scale. Rather, coalescence is the dominant process altering vesicle size-frequency distributions. Initial combination of bubbles spanning the size spectrum is replaced vertically by selective combination of only the largest bubbles near flow tops. This change in growth process is likely controlled by vertical viscosity changes within the cooling lava flow. The combination of these processes is responsible for the development of the visually and mathematically distinct textures found within vesicular basalt.

References Cited


About the Authors
Jason Turflinger, an undergraduate student-athlete, conducted this research in partial fulfillment of honors-program requirements at Indiana-Purdue, Fort Wayne.

Carl Drummond, assistant professor of geology at IUPW, a carbonate sedimentologist and stratigrapher by training, is deeply interested in the interpretation of magnitude-frequency relationships in natural systems and is committed to the concept of education of undergraduate scientists through their involvement in primary research projects.

Food for Thought
The critical fact is that a mass medium is no good whatsoever at conveying educated ideas; if it happens to convey a sophisticated idea, that's just an accident.
I think the French were perfectly right in trying to exclude U.S. television programs, because for the most part such programs are the ultimate realization of mass taste, and they are depraved and destructive. They are deeply destructive to American society, particularly to any effort to educate anyone in it. And yet the schools increasingly try to simulate TV culture, which is their worst betrayal.