Inferring Volcanic Degassing Processes from Vesicle Size Distributions

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Both power law and exponential vesicle size distributions (VSDs) have been observed in many different types of volcanic rocks. We present results of computer simulations and laboratory analogue experiments which reproduce these findings and show that the distributions can be interpreted as the product of continuous bubble nucleation resulting from non-equilibrium degassing. This ongoing nucleation causes the bubbles to evolve through an exponential size distribution into a power law size distribution as nucleation and growth progress. These findings may explain the apparent contradiction between present models of bubble growth in magmas, which predict that degassing in explosive eruptions is a non-equilibrium process, and models of conduit flow, which assume perfect equilibrium degassing. The process of continuous nucleation is the mechanism whereby the volcanic system maintains near-equilibrium in the case of rapid depressurization and slow volatile diffusion.

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Introduction

Several studies have investigated VSDs of volcanic rocks with the aim of deducing eruption parameters. Many different forms of VSD have been measured, including exponential [*Sarda and Graham,* 1990; *Mangan et al.,* 1993], and power law [*Gaonac'h et al.,* 1996a; *Simakin et al.,* 1999] with different mechanisms proposed to explain their formation. Exponential VSDs are explained on the basis of a steady-state process with constant nucleation and growth rates [*Marsh,* 1988]. Theoretical models of bubble growth in magmas [*Lyakhovsky et al.,* 1996], however, reveal that bubble growth rates are far from constant. A process of cascading coalescence has been proposed to explain the presence of power law VSDs in basaltic lavas [*Gaonac'h et al.,* 1996b]. We show here that both power law and exponential size distributions can be explained by a single mechanism of continuous nucleation, with the bubbles tending to pack efficiently and fill space. Figure 1 illustrates this process in natural, experimental and model samples. Representative VSDs from these samples are shown in figure 2.

Power law VSDs and their properties

Power law size distributions are described by the equation

$$N(r) \propto r^{-(d+1)} \Rightarrow N(>r) \propto r^{-d} \qquad (1)$$

where $N(r)$ is the number of objects of a size (radius) r, $N(>r)$ is the number of objects with a radius greater than r, and d is the power law exponent. We choose to use the cumulative form of equation 1, i.e. $N(>r)$ versus r, to express power law VSDs. This gives a more accurate estimate of d as it does not require the data to be binned, which can cause large uncertainties in the calculation of the exponent.

Power law distributions, unlike unimodal or exponential VSDs (equations 2 and 3), have no characteristic length scale and so no 'average' bubble size in the population. If the exponent d is between 2 and 3 (typical for volcanic rocks as we shall see) then the total volume of the bubbles is controlled mostly by the large bubbles, but the total surface area is controlled by the smallest size fractions [*Turcotte,* 1992]. It is therefore impossible to approximate both diffusive bubble growth (surface area controlled) and decompressive growth (volume controlled) successfully by assuming a monodisperse distribution.

Observations of power law VSDs in volcanic rocks

A wide range of volcanic eruption types have been found to produce rocks with power law VSDs. In Gaonac'h et al. (1996a), VSDs of ʻaʻā and pāhoehoe lavas from Etna were measured. The large bubbles were well described by a distribution with $d \sim 2.5$. Simakin et al. (1999) measured VSDs of experimentally generated samples, pumice and basaltic lavas and scoriae, and the combined data were shown to be described by a power law distribution with $d \sim 1.8$. We have re-analyzed images of pumices and basaltic scoria from Toramaru (1990) (figure 1b) and found that the VSDs of the scoria samples were in the form of a power law with $d \sim 2.7$, whereas the VSDs of the pumices were better described by an exponential relationship (equation 3).

Modelling the generation of power law VSDs

Analogue experiments

In order to investigate the effect of eruption conditions on the bubble size distribution we performed a series of analogue experiments. Solutions of gum rosin in acetone (GRA) were used as the analogue for hydrated magma [*Phillips et al.,* 1995]. The GRA solution is initially held at room temperature and pressure in a glass shock tube. By the bursting of a diaphragm which separates the shock tube from a vacuum chamber, the solution is instantaneously decompressed to 1 or 50 mbar. The acetone boils explosively and a foam flow results which expands up a shock tube at peak velocities from < 0.1 to 10 ms^{-1}. Solutions of 20, 25 and 30 wt.% acetone were used, representing initial viscosities of 1, 0.1 and 0.04 Pa s respectively. On degassing, the solution undergoes a viscosity increase of several orders of magnitude similar to that calculated for hydrated magmas during an eruption [*Phillips et al.,* 1995], ultimately producing a solid gum rosin foam. This foam is sectioned and photographed for image analysis (figure 1c). Over a wide range of experimental conditions the VSDs of the foam were found to be consistently in the form of a power law with an exponent typically between 2 and 2.5 (figure 3). High speed video camera footage reveals that nucleation occurs continuously throughout the degassing process, not in a single event.

Space-filling processes and the Apollonian packing

We propose that the power law VSDs in both the natural and the experimental samples are formed by a process of continuous nucleation, in which successive generations of bubbles nucleate in the melt pockets between existing bubbles. Each bubble depletes the surrounding melt in volatiles as it grows and so these melt pockets represent the least depleted regions and hence the most favourable locations for subsequent nucleation. The result of this concurrent nucleation and growth is analogous to an ideal mathematical fractal, the Apollonian packing (figures 1a and 2a).

Numerical modelling

A simple computer model was constructed to investigate this space-filling process in more detail. A first generation of bubble nuclei are placed at random locations in a 3-D domain and are allowed to grow according to a parabolic growth law, $r = \beta t^{1/2}$ [*Scriven,* 1959], where the growth constant β is related to the size of the 'zone of influence' of the bubble, i.e. the set of points which are closer to the bubble in question than to any other bubble (the Voronoi volume). The results of the model are, however, insensitive to the exact form of the bubble growth law. Subsequent generations of bubbles nucleate as far from these existing bubbles as possible (figure 1d).

The greatest influence on the form of the resulting VSD is the number of nucleation events, that is, the number of 'pulses' or bursts of nucleation we allow to occur as growth progresses (figure 4). We use discrete nucleation events in the model as an approximation to continuous and simultaneous nucleation and growth. The number of events is a measure of the length of the nucleation period relative to the growth timescale. A single nucleation event leads to a unimodal (Poisson) distribution [*Tuckwell,* 1988]:

$$N(r) \propto r^2 \exp(-\lambda r^3) \Rightarrow N(>r) \propto \exp(-\lambda r^3) \quad (2)$$

where λ is a constant related to the number density of bubble nuclei. For a small number (~ 3) of nucleation events, the model predicts an exponential size distribution:

$$N(r) \propto \exp(-r/r_0) \Rightarrow N(>r) \propto \exp(-r/r_0) \quad (3)$$

where r_0 is a characteristic bubble size. In the numerical model, exponential distributions always evolve into power law distributions with further nucleation events. After a total of 5 events the distribution is consistently power law. The exponent d is found to increase with the number of nucleation events, ultimately converging on a value close to that of the three-dimensional Apollonian packing (2.45 [*Anishchik and Medvedev,* 1995]). Around 7-10 nucleation events are required to produce an exponent of between 2 and 3, which is the range into which most natural samples fall. The effects of bubble coalescence are not considered.

Interpretation

The combined results of the analogue experiments and numerical modelling suggest that the presence of a power law or exponential VSD is indicative of a degassing system that cannot maintain equilibrium with its environment. If diffusive mass transfer of volatile molecules into the first bubble population nucleated is not rapid enough to allow the system to maintain a volatile concentration in the melt which is in equilibrium with the ambient pressure then further bubbles may nucleate in the volatile-rich melt pockets between bubbles [*Lyakhovsky et al.,* 1996]. Such nucleation behaviour has been observed or inferred in experiments simulating the degassing of silicate melts [*Navon et al.,* 1998; *Simakin et al.,* 1999]. The degassing of acetone in the GRA experiments is highly non-equilibrium; the volatile concentration in the solution immediately after expansion ceases is well above the equilibrium concentration. (The foam becomes sufficiently permeable to allow these residual volatiles to escape without any further expansion.) As a result of this non-equilibrium degassing continuous bubble nucleation occurs and a power law VSD is generated. Power law or exponential VSDs are to be expected whenever a system is forced far from equilibrium and physical parameters do not favour efficient degassing, i.e. for rapid depressurization, low initial nucleation density, and slow volatile diffusion. The exponent d is a measure of the number of nucleation events, or the length of the nucleation period relative to the timescale of growth.

Coalescence versus continuous nucleation

Our mechanism for producing power law VSDs by means of continuous nucleation does not incorporate the effects of coalescence. In an effusive eruption involving low viscosity magma, we might expect that degassing will be close to equilibrium, and so the likelihood of the occurrence of several nucleation events is much reduced. The mechanism of cascading coalescence [*Gaonac'h et al.,* 1996a] may be dominant in this case.

By contrast, in the case of explosive eruptions, especially involving acidic, highly viscous magma and rapid magma ascent rates, bubble growth models [*Proussevitch and Sahagian,* 1996] predict non-equilibrium degassing and so continuous nucleation may occur. Simakin et al. (1999) observed power law VSDs in samples produced during controlled experiments in which continuous nucleation occurred, but little or no coalescence took place. In our re-analysis of data from Toramaru (1990), we used his 'decoalesced' images (his figure 2) and discovered power law VSDs. We interpret these pre-coalescence power law VSDs to be the result of multiple nucleation events.

Implications for modelling volcanic processes

These findings may resolve an apparent contradiction in current numerical models of explosive volcanic eruptions. Conduit flow models [*Mader,* 1998; *Melnik and Sparks,* 1999] are usually based on the assumption that degassing is an equilibrium process. By contrast, bubble growth models [*Proussevitch and Sahagian,* 1996] assume a single nucleation event and a monodisperse VSD and predict non-equilibrium degassing under the conditions of an explosive eruption, in agreement with our observations. However, highly non-equilibrium conditions would lead to continuous nucleation. This would increase the efficiency of the degassing process and allow the system to approach equilibrium more readily. The resolution of the contradiction between these two rival groups of numerical models rests in the relaxation of the respective assumptions of equilibrium conditions and a single nucleation event.

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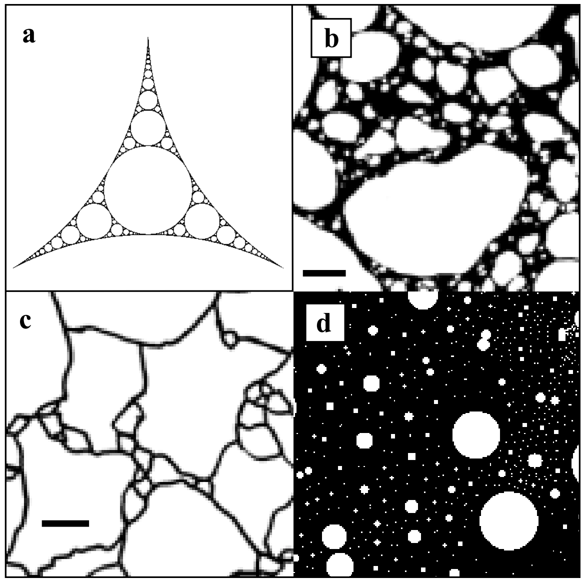

Figure 1. Illustration of space-filling behaviour in different systems. Several distinct bubble generations are visible with smaller bubbles filling the spaces between larger ones. For power law VSDs, the 2-D size distribution of object (bubble) slices is also a power law with an exponent one less than that of the 3-D VSD. (a) Two-dimensional Apollonian packing. This is by definition the densest packing of circles in a plane. (b) Thin section of scoria from a basaltic sub-plinian eruption of Izu-Oshima, Japan (reproduced from Toramaru, 1990). Scale bar is 0.75 mm. (c) Gum rosin foam (see text and figure 3). Scale bar is 0.2 mm. The foam vesicularity is very high ($\sim 90\%$) and so the bubbles are in the form of polyhedral cells. (d) Image of a slice through 'foam' produced in the numerical model described in the text and in figure 4.

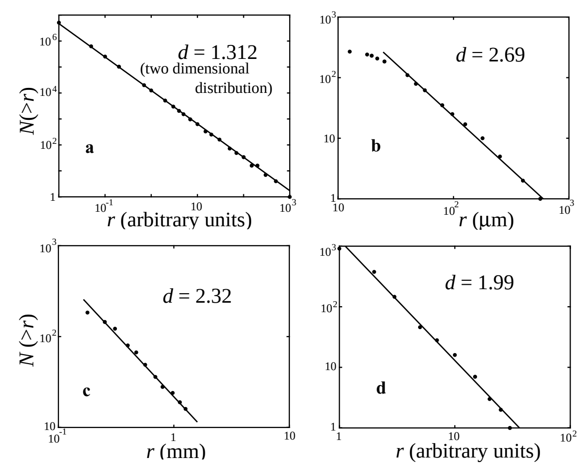

Figure 2. Bubble size distributions of the images in figure 1. Note that the VSD of the Apollonian packing (a) is a 2-D distribution. The VSD of the 3-D equivalent (the densest packing of spheres) has $d \sim 2.45$. All other VSDs represent the distribution of bubble sizes in 3-D.

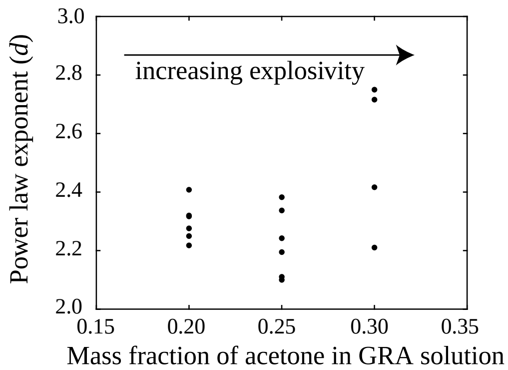

Figure 3. The variation of the power law exponent d with the initial acetone content of the gum rosin and acetone (GRA) solution in the analogue experiments. Errors on each point are around ± 0.2. The exponent is insensitive to the conditions of the experiment.

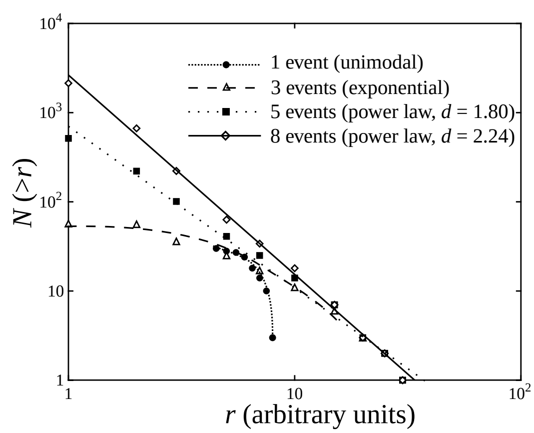

Figure 4. Results of a numerical model which simulates the space-filling nucleation and growth process. The form of the VSD is controlled by the number of nucleation events which occur during bubble growth.