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Impact vesiculation – a new trigger for volcanic bubble growth and degassing

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Abstract

We highlight a potentially important trigger for bubble growth and degassing in volcanic bombs. We have successfully triggered bubble growth in previously unvesiculated samples of silicate melt during experiments to simulate volcanic bomb impact, by firing pellets at, and dropping weights onto, melt samples. We call this phenomenon “impact vesiculation”. Further work is required on real volcanic bombs to establish the extent to which impact vesiculation occurs in nature. However, our experiments are sufficient to demonstrate that impact vesiculation is a viable processes and should be borne in mind in analysis of bubble populations and degassing histories of bombs and spatter-fed lava flows. Degassing caused by impact vesiculation can occur only at ground-level, so any attempt to calculate the amount of erupted gas available for transport high into the atmosphere by convection above the source of a fountain-fed lava flow that is based on subtracting the volatile content of fluid inclusions from the volatile content of the resulting lava flow would be an overestimate if significant impact vesiculation has occurred.

1 Introduction

It is a commonplace observation that a can of beer that has been dropped or shaken should not be opened for a while. This is because violent agitation leads to cavitation-based bubble nucleation (see Appendix A). Unless time is allowed for the gas in these bubbles to redissolve, whoever opens the can is likely to receive an explosive soaking as soon as the bubbles are permitted to expand.

Bubbles in fragmented erupted magma are usually regarded as being a mixture of those that grew during ascent from depth and/or during shallow storage, and those that grew during the eruption process (e.g., Sparks and Brazier, 1982; Mangan et al., 1993; Blower et al., 2002). Similarly, Walker (1989) regarded vesicles in spongy pahoehoe to be inherited from the vent, although their size characteristics are a result of coalescence after cessation of flow advance. Earlier and more violent coalescence of bubbles in the conduit or below may sometimes lead to explosive fragmentation and the eruption of bombs (Vergniole and Jaupart, 1986, 1990).

Here we suggest a late-stage mechanism of bubble nucleation inside a bomb when it hits the ground, analogous to the dropped beer-can situation, which we term "impact vesiculation". We became aware of this possibility during examination of spatter bombs from the unusually violent 11 September 1930 lava fountain eruption of Stromboli (Rittmann, 1931; Barberi et al., 1993). Considerably more field- and lab-work would be required to prove that these particular bombs indeed experienced impact vesiculation, although it certainly offers a plausible explanation for aspects of their texture, which we describe briefly later.

However, our main purpose is to report preliminary experiments in which we have successfully caused impact vesiculation in the laboratory, thus demonstrating that it is a viable process (notably within bombs ejected during strombolian or Hawaiian-style fire-fountaining), and to draw attention to some of the implications.

2 Impact vesiculation triggers

In what follows, we use terms according to the following definitions: *nucleation* refers to the creation of a bubble from a state in which the bubble did not yet exist; *bubble growth* refers specifically to the growth of bubbles that have already nucleated; *vesiculation* is a less specific term that can mean nucleation plus growth, but can also be used when it is unclear whether a process actually caused nucleation or merely stimulated previously-nucleated sub-microscopic bubbles to grow to visible size.

There are two plausible explanations for the phenomenon of impact vesiculation in volcanic bombs, both of which could act either as nucleation triggers or merely as growth-triggers for sub-microscopic pre-existing bubbles. One is simply that rupture of a bomb's chilled rind ("opening the can of beer") upon impact with the ground releases confining pressure in the bomb interior, thus allowing a new episode of nucleation and/or bubble growth. The other is that the shock of the impact ("dropping the can of beer") acts as the stimulus. The triggering forces are much stronger for the latter, so we believe this to be of especial importance. We speculate that the rarefaction pulse that must follow the impact-induced compression pulse leads to cavitation within the fluid volume of the bomb, causing bubble nucleation. It is in order to test this hypothesis that we conducted the experiments described below.

In a magma, as in any fluid, bubble nucleation may occur either homogeneously (within a uniform, uncontaminated melt) or heterogeneously (thanks to the thermodynamic advantage of nucleating against a solid/liquid interface, such as upon a microlite). The former is thought to require greater supersaturation, but Cashman et al. (2000) suggest that a basaltic magma's exsolution history is likely to lie "somewhere between the two end member models". Cavitation in fluids as a result of shearing or negative pressure is a well-established phenomenon (e.g., Talanquer and Oxtoby, 1995; Kinjo and Matsumoto, 1998). The decompression necessary to trigger bubble nucleation in saturated rhyolitic magmas has been shown experimentally to be tens of megapascals for homogeneous nucleation and less than one megapascal for heterogeneous nucleation (Hurwitz and Navon, 1994; Mangan and Sisson, 2000; Lensky et al., 2004). We are not aware of any previous suggestion that a transient drop in pressure such as that associated with an impact shock could trigger vesiculation in magma, although an analogous phenomenon called "acoustic cavitation" is well-known in other fluids (e.g., Young, 1989; Harkin et al., 1999).

Brodsky et al. (1998) showed how earthquake vibrations can pump up the volume of pre-existing bubbles in silicate magma by the process of rectified diffusion. This is a sustained process, and not a viable explanation for vesiculation caused by impact shock.

3 Impact vesiculation experiments

We performed a series of experiments, which has demonstrated that impact vesiculation can occur within silicate magma. In common with most bubble nucleation studies using silicate melts (e.g., Hurvitz and Navon, 1994; Simakin et al., 1999; Magnan and Sisson, 2000; Lensky et al. 2004; Mangan et al., 2004), our experimental material was a rhyolite of well-characterised properties, rather than a basalt that would require higher temperatures and be more difficult to control.

We chose a microlite-free obsidian rhyolite from the Monte Pilato breccia, Lipari (Pichler, 1980; Sheridan et al., 1987), which required no sample preparation other than drilling to make cylindrical cores. This has a FTIR-determined water content of about 0.15%, which is sufficient to allow vesiculation to occur without the need to artificially hydrate the sample beforehand.

We heated 16 mm diameter, 15–18 mm long, cylinders of rhyolite in a removable, hinged furnace, taking about two hours to heat from room temperature to 900°C. At this temperature our sample was far above its glass transition temperature, which we measured using differential scanning calorimetry (e.g., Gottsmann and Dingwell, 2001, 2002) to be 678°C, and was a supercooled liquid. Strictly speaking it was not molten because it was below the solidus temperature for rhyolite, and had it contained any microlites these would have remained fully crystalline. We found that our samples would eventually and rapidly expand into a foam, if held at 900°C, by the sudden exsolution of volatiles (chiefly water). In our experiments we interrupted this maturation process before foaming had begun by removing the furnace from around the sample and immediately subjecting the sample to an impact.

We tried two kinds of impact, both of which proved capable of triggering bubble growth in as-yet unvesiculated samples: impact by an airgun pellet at a speed of about 250 $\mathrm{m\,s^{-1}}$ and impact by a metal cylinder dropped from a height of 2.4 m with a calculated impact speed of about 6.8 $\mathrm{m\,s^{-1}}$. Despite the very different impact speeds, the kinetic energy delivered to the sample in both regimes was similar: about 13 J for the airgun pellet versus 7.6 J for a steel drop-cylinder and 1.9 J for an aluminium drop-cylinder. Airgun pellet impacts knocked our samples from their podium, without shattering them. High speed video images show samples beginning to swell upon impact, and the degree of vesicle-induced expansion was often clearly greater in the region where the pellet had struck (Fig. 1).

Drop-cylinder impacts fragmented our samples. The heavier steel cylinder left no fragments greater than 5 mm across, and reduced 60% of the sample to powder. The shards were relatively pale grey, because of the abundance of vesicles generated within them. Impact by the less-heavy aluminium cylinder resulted in only 35% powder and fewer, larger and darker shards. These too were found to include vesicles that had been absent before heating, though smaller than in the previous case. An unimpacted control sample that we quenched after an identical heating regime contained very few, and smaller, vesicles (Fig. 2).

We do not claim to have replicated all the conditions experienced by a spatter bomb striking the ground. Our samples were smaller, and bubble growth would have been inhibited by the greater viscosity of rhyolite and terminated by more rapid cooling than would be experienced in a basaltic bomb interior. Bubbles must have grown in size chiefly by diffusion of gas into them, as there would have been insufficient time before cooling to allow bubbles to migrate towards one another and coalesce (e.g., Burgisser and Gardner, 2005). Moreover, the propagation of an impact-shock through a spatter bomb would clearly differ in detail from the shock propagation in our experiments.

However we have demonstrated that impacts can trigger vesiculation in silicate magma. Shock-induced impact vesiculation is therefore a plausible explanation for the bubbles in bomb interiors, and should be considered when trying to interpret the vesiculation history of volcanic bombs and large spatter clasts. We note that our laboratory samples were all about 0.007 kg, so the impact energy per m^3 of rock was in the range 7×10^5 to 5×10^6 J m^{-3}. This is comparable to 3.9×10^6 J m^{-3} experienced by a bomb hitting the ground at 50 m s^{-1} and 1.6×10^7 J m^{-3} at 100 m s^{-1} (see Appendix A).

4 A possible example: Stromboli 1930 bombs

The size and dispersal of Stromboli 1930 bombs and historical descriptions of the eruption suggest likely impact speeds in the range 70–120 m s^{-1}. Even in the field it can be observed that there are markedly different populations of vesicles in the rinds and cores of spatter (cowpat) bombs from this eruption (Fig. 3). The chilled rind, approximately 1 cm in thickness, is distinctly less vesicular than the interior and is characterized by isolated vesicles up to 4 mm in diameter. Some of these bubbles are stretched or flattened parallel to the bomb margin. In contrast, bomb interiors are expanded to foam (though without discernable permeability) and bubbles here tend to be smaller and lack obvious signs of deformation. Figure 4 shows analyses of bubble sizes measured in the figure sample. It confirms that bubbles larger than 0.5 mm are very rare in the interior but common in the rind, and also that there are far more bubbles smaller than 0.5 mm in the interior than in the rind. Our five profiles crossed only five bubbles smaller than 0.5 mm in the outermost 5 mm, whereas there were 24 in the 5–10 mm depth interval and about 50 each in the 10–15 mm and 15–20 mm depth intervals.

Very small bubbles are rare: examination in thin section reveals that there are fewer than three bubbles of less than 0.1 mm apparent diameter per mm^2. The groundmass is of clear glass in the rind and turbid glass in the interior. Phenocrysts of euhedral augite up to 1–2 mm in size and much rarer plagioclase occur throughout. Dispersed microlites of plagioclase about 0.1 mm in length are present too, and are considerably more abundant in the interior than in the rind. We recognise that microlite growth would have increased the volatile content of the remaining melt and could therefore have acted as an additional stimulus to bubble growth, and also that the reduction in volatile content of the melt because of the growth of bubbles could have caused some of the microlites to grow in the first place (Simakin et al., 1999; Cashman and Blundy, 2000; Couch et al., 2003). Irrespectively, the presence of these microlites does not undermine the feasibility and importance of the impact vesiculation triggers suggested above.

We suggest the following plausible interpretation of the bubble populations. The earliest bubbles grew within the magma conduit (e.g., Lautze and Houghton, 2005, 2007). Expansion may have continued during ejection of the spatter. Plastic deformation of the rind during flight and upon landing is manifested by the distortion of some of these bubbles. The absence of similarly-sized bubbles of the same early-formed population in bomb interiors may result from resorption during ductile deformation. Irrespective of this, we interpret the distinctly greater vesicularity of bomb interiors to be at least partly a result of a new episode of impact-triggered bubble growth that happened after the bomb landed. At this stage, new bubbles could not form in the rind, because the rind was already solid (viscoplastic), and this explains the almost total absence of small bubbles in the rind. Late-forming bubbles in Stromboli bomb interiors would have been created by the exsolution of mainly H_2O and SO_2, rather than CO_2 which exsolves at much greater depths and pressures (Allard et al., 1994).

5 Implications and conclusions

We propose that impact vesiculation could be the origin of some of the bubbles in volcanic bombs. It could even be the cause of post-depositional expansion that is characteristic of breadcrust bombs, in which impact vesiculation triggered by impact shock in the molten interior would provide the expansion mechanism commonly assumed or implied (e.g. Sigurdsson et al., 2000; Francis and Oppenheimer, 2004) to cause the breadcrust-like rupture of the chilled rind.

Furthermore, bombs falling from fire-fountains are likely to be prone to impact vesiculation, even when the fallen spatter quickly agglutinates into a clastogenic lava flow. Given the growing consensus that continental flood basalts are a product of fire-fountain eruptions (e.g., Thordarson and Self, 1998; Sumner et al., 2005), this has implications for studies of volcanic degassing and its climatic influence. For example, impact vesiculation releases gas at ground-level only. Thus any attempt to estimate the amount of sulfur injected high into the atmosphere by subtracting the sulfur content of clastogenic lava from the sulfur content of melt inclusions would result in an overestimation. It is therefore especially important to base such calculations upon the sulfur contents of quenched eruption products such as fine tephra, after the manner of Thordarson and Self (1996) and Thordarson et al. (2003).

Further studies are now required on the phenomenon of impact vesiculation. Experimental stimulation of impact vesiculation should be attempted using samples of a range of silica and volatile contents. Eruption ejecta should be analysed to determine whether small scoria with low terminal fall speed retains a greater volatile content than larger, potentially impact-vesiculated, ejecta, and bubble size distributions in bombs should be re-examined with impact vesiculation in mind.

Finally, our proof that impact vesiculation can happen in silicates raises the possibility that shock waves associated with large (magnitude 7 and above) tectonic earthquakes, which sometimes appear to act as the triggers for volcanic degassing or eruption (Linde and Sacks, 1998), could do so by stimulating bubble nucleation. However, in such a case, the opening of fractures (Moran et la., 2002), the stimulation of bubble growth (Brodsky et al., 1998) or simply the shaking loose of previously-exsolved volumes of gas would appear to be equally viable options.

Appendix A

Mathematical background

There is a fundamental dimensionless number in fluid dynamics called the Euler number or Cavitation number, *Ca*, which provides a way of comparing the potential for impact vesiculation to occur. *Ca* is defined as $(P_a - P_v)/(^1/_2 \rho v^2)$, representing the difference between ambient pressure and vapour pressure, divided by the "dynamic pressure" $^1/_2 \rho v^2$, where ρ is fluid density and v is usually some measure of speed (Brennen, 1995; Arndt, 2002). For any given situation, when *Ca* falls below an empirical threshold, cavitation will occur. It is reasonable to use the concept of *Ca* as a measure of the impetus for impact vesiculation.

In the case of a dropped (or shaken) beer can, we can equate $^1/_2\rho v^2$ to the kinetic energy imparted to unit volume of the can's contents. In the case of magma impact vesiculation, we can relate $^1/_2\rho v^2$ to the kinetic energy transferred (whether by agitation or shock) to unit volume of a clast's interior. Given that the impact energies per unit volume of our field examples are similar to (but larger than) in the laboratory examples, and that the ambient minus vapour pressure term in the numerator would be similar in both situations, we can infer that *Ca* in our field examples is similar (to but smaller than) *Ca* in our laboratory examples.

Thus, impact vesiculation would seem to be at least as favoured by the field situation as in our laboratory simulations. We suggest that, at least for bubble nucleation (as opposed to growth), it is reasonable to overlook viscosity differences, but in any case these would make it easier for bubbles to form in low viscosity basalt than in higher viscosity rhyolite.

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Fig. 1. Lipari rhyolite cylinders used in our experiments. Left: an unheated, unimpacted control sample. Centre: unused “diablo” airgun pellet. Right: sample that was heated to 900˚C and then shot with airgun pellet. This caused impact vesiculation throughout, but especially in the region closest to the where the pellet struck (the left-hand edge as seen here). Scale bar is graduated in mm.

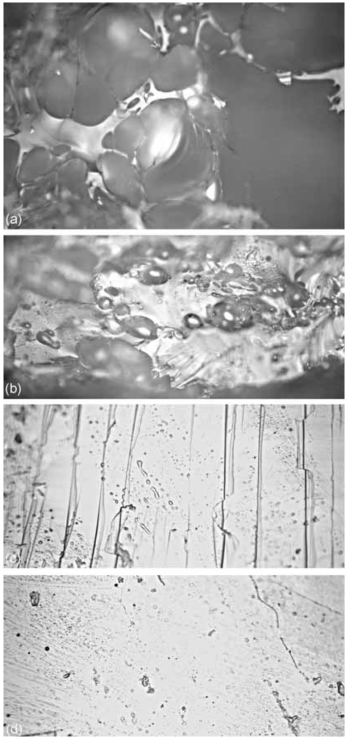

Fig. 2. Reflected light photomicrographs of vesicles in Lipari rhyolite heated to 900°C. Field of view 0.68 mm wide in each case. **(a)** vesicles induced by impact of an airgun pellet (13 J); largest bubble about 400 μm in diameter. Note thin septae between bubbles frozen in the act of coalescence **(b)** vesicles induced by impact of steel drop-cylinder (7.6 J); largest bubble about 100 μm in diameter. **(c)** vesicles induced by impact of aluminium drop-cylinder (1.9 J); largest bubble about 30 μm in diameter. Prominent lines are patterning on a conchoidal fracture surface. **(d)** an identical sample quenched after the same heating regime; largest bubble (less prominent than surface pits left by imperfect polishing of the sample) about 10 μm in diameter. (a–c) fractured surfaces, (d) polished surface.

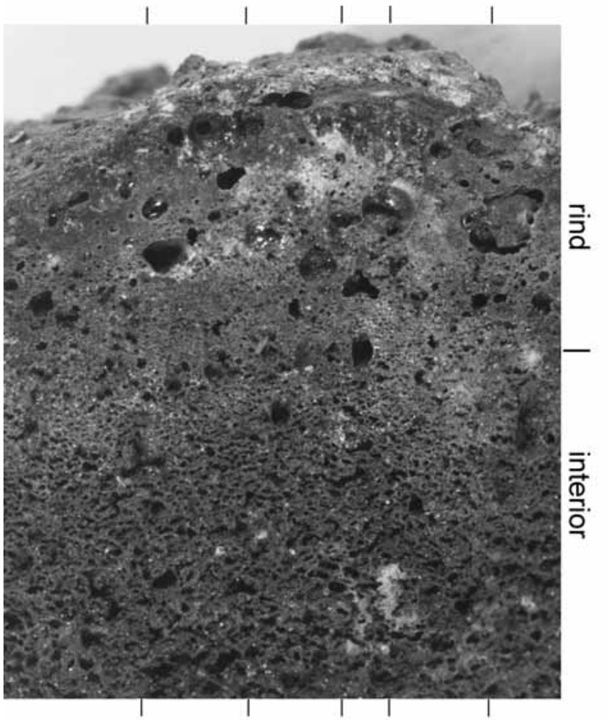

Fig. 3. Cross-section through the outer part of a 1930 Stromboli bomb. The area shown is a broken (not sawn) surface and measures 23 mm from top to bottom. Note the abundant bubbles <0.5 mm in diameter in the interior, which may represent impact vesiculation, and are a population that is absent from the chilled rind. Tick marks at top and bottom edges mark the lines of five bubble analysis traverses that are plotted in Fig. 4.

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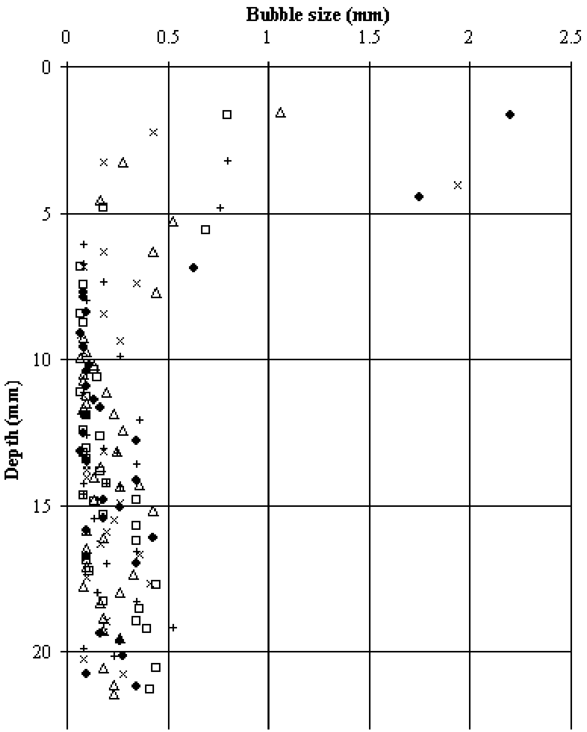

Fig. 4. Bubble sizes along five traverses perpendicular to the margin of the Fig. 3 sample. Profiles were chosen so that some intersected the largest bubbles in the rind whereas others avoided them. Every discernable bubble encountered in each traverse is plotted, using a different symbol for each traverse. Measurements were made on a high-resolution version of Fig. 3, with a lower bubble-size detection limit of 0.08 mm. The dip in maximum bubble size near 10 mm depth corresponds to the visually distinct boundary between rind and interior.