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Experimental modelling of fragmentation applied to volcanic explosions

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ABSTRACT

Explosions during volcanic eruptions cause fragmentation of magma and host rock, resulting in fragments with sizes ranging from boulders to fine ash. The products can be described by fragment size distributions (FSD), which commonly follow power laws with exponent D. The processes that lead to power-law distributions and the physical parameters that control D remain unknown. We developed a quantitative experimental procedure to study the physics of the fragmentation process through time. The apparatus consists of a Hele-Shaw cell containing a layer of cohesive silica flour that is fragmented by a rapid injection of pressurized air. The evolving fragmentation of the flour is monitored with a high-speed camera, and the images are analysed to obtain the evolution of the number of fragments (N), their average size (A), and the FSD. Using the results from our image-analysis procedure, we find transient empirical laws for N, A and the exponent D of the power-law FSD as functions of the initial air pressure. We show that our experimental procedure is a promising tool for unravelling the complex physics of fragmentation during phreatomagmatic and phreatic eruptions.

1. Introduction

Explosive volcanism can have severe impact on modern society. A good example is the April 2010 eruption of Eyjafjallajökull Volcano in Iceland, which produced large quantities of fine ash that disrupted air traffic in Europe (Gudmundsson et al., 2010; Sigmundsson et al., 2010; Petersen, 2010). Despite this, the processes governing explosive volcanism and associated fragmentation are poorly understood due to their high kinetics and violent dynamics.

Explosive volcanic eruptions are separated into four main types: low viscosity magmatic, high viscosity magmatic, phreatomagmatic and phreatic. The magmatic explosive eruptions in low and high viscosity magmas are commonly caused by expanding bubbles, leading to large overpressures that fragment the magma close to the surface. The explosive origins of both phreatomagmatic and phreatic eruptions is due to the rapid vaporisation of water (or ice) in direct or thermal contact with a nearby heat source, *e.g.* magma; the vaporisation of water results in sudden volume increase, resulting in pressures that are high enough to pulverize rocks (Smellie, 2002). The main difference between these two latter types of explosions relates to the nature of the fragmented material, *i.e.* country rock only for phreatic and both country rock and magma for phreatomagmatic. Fragments resulting from these violent processes have sizes ranging from coarse-grained (volcanic bombs) to very fined grained (ash) material (Sheridan, 1980; Lorenz, 1985). In this paper, we focus mostly on phreatomagmatic and phreatic explosions.

Because of their wide range of sizes, it is meaningless to describe the products of volcanic explosions by an average value. Instead, they can be described by a fragment size distribution (FSD), generally defined as a cumulative frequency histogram, *i.e.* the number N of fragments larger than a size L (*e.g.*, Kaminski and Jaupart, 1998; Rust and Cashman, 2011). Field studies show that the fragment size distributions of deposits produced from explosive volcanism can be described by power laws (Kaminski and Jaupart, 1998; Rust and Cashman, 2011). Thus they can be written

$$N\,(>L) \propto L^{-D}, \tag{1}$$

where L is a given fragment size, $N\ (>L)$ is the number of fragments larger than L, and D is the exponent of the power law. In a log–log plot, the power law FSD for $N\ (>L)$ against L appears as a straight line of slope $-D$.

Power-law distributions are scale invariant (Mandelbrot, 1983; Hergarten, 2002). The value of D expresses the relative quantity of small fragments with respect to large fragments. For example, a larger value of D means more small fragments per large fragment. Thus D measures the efficiency of fragmentation and may contain crucial physical information about the fragmentation process (Turcotte, 1986; Kaminski and Jaupart, 1998). Jébrak (1997),

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for instance, studied hydrothermal breccia in veins or ores, and showed that highly energetic events have a higher value of D than those with lower energy. Field studies of volcanic deposits, however, usually yield only the fragment size distributions of the final product of a combination of fragmentation, transport and deposition, and very little information of the processes at the fragmentation source is reachable. Other approaches are thus needed.

One such approach are experiments, such as Molten Fuel Coolant Interaction (MFCI) experiments (*e.g.*, Zimanowski et al., 1991, 1997a, 1997b; Grunewald et al., 2007), which mimic phreatomagmatic explosions at laboratory scale. These experiments are performed by mixing water with molten volcanic rock, causing an explosion that fragments the melt. At the end of an experiment, the fragments produced are collected and their fragment size distribution measured. In general, these experiments show a power law distribution (Zimanowski et al., 1991, 1997b). However, only the final products are available for analysis, and the mechanism whereby the power law arises remains unknown.

Fragmenting volcanic rocks in a fragmentation bomb (*e.g.*, Spieler et al., 2003, 2004; Kueppers et al., 2006a, 2006b; Koyaguchi et al., 2008; Kremers et al., 2010; Alatorre-Ibarguengoitia et al., 2011; Perugini and Kueppers, 2012) is another useful method. These experiments mimic magmatic eruptions of a highly viscous bubbly magma and also produce power law fragment size distributions. Kueppers et al. (2006a) and Perugini and Kueppers (2012) showed that the exponent D of the power laws is linearly correlated with the potential energy for fragmentation. Nevertheless, just as in the MFCI experiments, only the final fragment size distribution is available, and direct observations of the transient FSD is not possible.

Recently, *in situ* monitoring of magma fragmentation in laboratory experiments became possible with the use of a high-speed camera, and a mathematical model that explained the experimental results has been developed (Fowler et al., 2010; McGuinness et al., 2012). Although these studies represent substantial advances in our understanding of fragmentation processes, the small number of fragments is insufficient to study the FSD of the fragmented material.

Other recent studies have been conducted with high-speed cameras. Dürig et al (2012a, 2012b) and Dürig and Zimanowski (2012), for example, focused on the fracture dynamics and the energy dissipation of fractures in glass. They do not, however, study the fragment size distributions produced in their experiments. Kadono and Arakawa (2002) also used a high speed camera to monitor the development of fragmentation in a glass plate triggered by a high velocity impact. They calculated the evolution of the FSD, and found that the exponent D increased through time. The input energy of the impactor, however, was not controlled so they were unable to derive empirical laws for D as a function of the physical parameters of the system.

Fragmentation processes of solids have also been studied through theoretical modelling. A classical model known as *Geometric Fragmentation Theory* (GFT) was studied by Grady and Kipp (1985) and Grady (2006). This model assumes that fragmentation is a statistical phenomena corresponding to a random separation of a domain. In contrast, Brown (1989), Wohletz et al. (1989), and Wohletz and Brown (1995) suggested a model called *Sequential Fragmentation Theory* (SFT), which assumes that the fragmentation process occurs through a successive series of discrete events. Wohletz et al. (1989) applied the SFT theory to volcanic deposits, and argued that this theory can explain the observed FSD. Both GFT and SFT, however, are strictly statistical and therefore not adequate for understanding the physics of the fragmentation process.

Yet another model was suggested by Åström (2006), who consider fragmentation as a consequence of the propagation and merging of sets of fractures. This model describes the FSD as a combination of a power law term and an exponential term, where the first describes the small fragments and the latter the large ones. The large fragments are assumed to be produced from the large main fractures, while the small fragments are produced from small fracture-branches from the main fractures. While this model provides a physical explanation for the fragmentation process, it remains purely theoretical, and experimental or observational confirmation is lacking.

Despite the many studies of fragmentation, some fundamental questions remain. What is the physics that governs the fragmentation process? How does fragmentation occur through time? What are the mechanisms responsible for the power law fragment size distributions? What physical laws govern the exponent D? Addressing these questions, and applying them to phreatomagmatic and phreatic explosions, requires a physical system that allows for (1) *in situ* and high frequency observations to monitor the development of fragmentation through time, (2) quantitative analysis to calculate fragmentation parameters such as D, and (3) controlling the input physical parameters to deduce the empirical laws governing the fragmentation process. In this paper, we present a new experimental apparatus that achieves these three requirements. From preliminary experimental results, we show that this system allows us to extract empirical laws of transient fragmentation processes.

2. Methods

2.1. Experimental setup

The experiments were performed in a vertically oriented Hele-Shaw cell, *i.e.* a volume contained between two glass plates separated by a small gap. The cell is 60 cm in width and height; the gap between the two glass plates is 0.5 cm (Fig. 1).

The material used to represent the solid is a crystalline silica flour, produced by Sibelco, in Belgium, and sold under the name M400. The mechanical properties of the silica flour have been measured by Galland et al. (2009) and Galland (2012). The average grain size is ≈15 μm, and the grains are angular (Galland et al., 2006), so that they interlock when compacted. On a macroscopic scale, the silica flour is a cohesive Mohr–Coulomb material, whose cohesion C and tensile strength T are dependent on the compaction. It is therefore necessary to control the compaction of the flour before each experimental run. We do so by fixing a high frequency vibrator (Houston Vibrator model GT-25) to the cell. A load is placed on top of the flour during vibration to make sure that the surface of the layer remains flat. During vibration, the volume of the material decreases, *i.e.* the flour compacts, until it reaches a desired volume. This procedure allows for a good control on the density (1050 $\mathrm{kg\,m^{-3}}$). At this density, we measured the cohesion C of the silica flour and its friction coefficient μ at 369 ± 44 Pa and 0.81 ± 0.06, respectively (Galland et al., 2009; Galland, 2012). The value of μ corresponds to an angle of internal friction $\Phi \approx 39°$. The cohesion value is, within errors, the same as that measured by Galland et al. (2006), who also measured the tensile strength $T \approx 100$ Pa.

A tube of length 490 mm and inner diameter 4 mm connects a 5-litre pressure tank to the cell (Fig. 1). The pressurized air contained in the tank is injected into the flour through an inlet 25 mm above the bottom of the cell; the inner diameter of the inlet is 2 mm. The pressure within the tank at the start of the experiment was controlled by a pressure gauge. A fast electronic valve (Actuator, solenoid valve, opening time of 0.1 seconds to fully open) releases the pressurized air from the tank into the cell (which is at ambient pressure). The time it takes to empty the tank is roughly 1–2 seconds, depending on the initial pressure.