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Lab-scale ash production by abrasion and collision experiments of porous volcanic samples

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ABSTRACT

In the course of explosive eruptions, magma is fragmented into smaller pieces by a plethora of processes before and during deposition. Volcanic ash, fragments smaller than 2 mm, has near-volcano effects (e.g. increasing mobility of PDCs, threat to human infrastructure) but may also cause various problems over long duration and/or far away from the source (human health and aviation matters). We quantify the efficiency of ash generation during experimental fracturing of pumiceous and scoriaceous samples subjected to shear and normal stress fields. Experiments were designed to produce ash by overcoming the yield strength of samples from Tenerife (Canary Islands, Spain), Sicily and Lipari Islands (Italy), with this study having particular interest in the <355 μm fraction. Fracturing within volcanic conduits, plumes and pyroclastic density currents (PDCs) was simulated through a series of abrasion (shear) and collision (normal) experiments. An understanding of these processes is crucial as they are capable of producing very fine ash (<10 μm). These particles can remain in the atmosphere for several days and may travel large distances (~1000s of km). This poses a threat to the aviation industry and human health. From the experiments we establish that abrasion produced the finest-grained material and up to 50% of the generated ash was smaller than 10 μm. In comparison, the collision experiments that applied mainly normal stress fields produced coarser grain sizes. Results were compared to established grain size distributions for natural fall and PDC deposits and good correlation was found. Energies involved in collision and abrasion experiments were calculated and showed an exponential correlation with ash production rate. Projecting these experimental results into the volcanic environment, the greatest amounts of ash are produced in the most energetic and turbulent regions of volcanic flows, which are proximal to the vent. Finest grain sizes are produced in PDCs and can be observed as co-ignimbrite clouds above density currents. Finally, a significant dependency was found between material density and the mass of fines produced, also observable in the total particle size distribution: higher values of open porosity promote the generation of finer-grained particles and overall greater ratios of ash. While this paper draws on numerous previous studies of particle comminution processes, it is the first to analyze and compare results of several comminution experiments with each other in order to characterize these mechanisms.

Introduction

Ash generation in volcanic environments

Explosive volcanic eruptions produce clasts of variable sizes in many different ways. Within a conduit, rising magma decompresses forcing dissolved volatiles to exsolve into gas bubbles, ultimately forming overpressurized foam (Alidibirov and Dingwell, 1996). During further ascent, bubbles will try to expand due to on-going decompression. In multiphase or SiO_2-rich magmas, vesicle expansion competes against viscous resistance of the liquid. When the pressure difference between bubbles and liquid exceeds the yield strength of the material, the strain rate will cause it to break into fragments. A primary fragmentation process is the combination of rapid magma decompression, bubble overpressure (Zhang, 1999; Melnik et al., 2005), explosive vesiculation (Sparks, 1978) and strain-induced fragmentation (Dingwell, 1996; Papale, 1999). At failure, magma changes from being a continuous liquid containing gas bubbles (and crystals) to being a continuous body of gas containing droplets of the magma (pyroclasts). A stream of gas and pyroclasts will exit the vent, cooling during interaction with the atmosphere. Once gravity forces overcome buoyancy of the rising plume, parts of the plume can collapse and transform to ground-hugging pyroclastic density currents (PDCs), a two-phase mixture of gas and volcanic clasts (Parfitt and Wilson, 2008).

Ash, particles <2 mm generated by volcanic processes (Fischer, 1961; Schmid, 1981; Fischer and Schmincke, 1984), can be generated by a plethora of processes inside or outside the volcanic edifice

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(Dingwell et al., 2012). The most prominent processes are primary fragmentation within the conduit (e.g. Walker, 1981; Kueppers et al., 2006; Rose and Durant, 2009) and secondary comminution (processes where solid materials are reduced in size) within conduits, jets, plumes or PDCs (e.g. Walker, 1981; Taddeucci and Palladino, 2002; Cagnoli and Manga, 2003; Spieler et al., 2003; Schwarzkopf et al., 2007; Dufek and Manga, 2008; Dufek et al., 2009; Evans et al., 2009; Rose and Durant, 2009; Dawson et al., 2011; Manga et al., 2011; Dufek et al., 2012; Kueppers et al., 2012, & 2014a).

In this study, we investigate the role of comminution in determining the particle size distribution of volcanic deposits. Based on the terminal fall velocities of sedimenting particles and Stokes' Law, Rose and Durant (2009) predict atmospheric residence times of >30 min for ash (<2 mm), >3 h for fine ash (<355 μm) and >10 days for very fine ash (<10 μm). Both fine and very fine ash can, hence, travel far from the vent and pose a hazard to aviation industry (very fine ash entering and melting in jet turbines and causing failure, e.g. Casadevall, 1994; Kueppers et al., 2014b) and human or animal health (respiratory illness, contamination of drinking water etc. e.g. Calder et al., 1999; Cole et al., 2002; Horwell and Baxter, 2006; Edmonds et al., 2006; Stewart et al., 2006; Sword-Daniels et al., 2010; Wilson et al., 2012).

Fine-grained ash dramatically increases the mobility of PDCs: within dense granular flows, fine grains tend to fill inter-grain spaces and thus decrease hydraulic permeability, which contributes to retain pore fluid pressure (Roche, 2012). Within dilute PDCs, fine ash transported in turbulent suspension increases a flow's bulk density and thus its competence and momentum. Suspended load currents can detach from the dense granular basal layers (flow-stripping, Douillet et al., 2013a), surmount topography more easily (Dufek and Manga, 2008), reach farther and present greater hazard (e.g. Miller and Smith, 1977; Walker, 1981; Calder et al., 1999; Dufek and Bergantz, 2007; Dufek et al., 2009). Scaling analysis suggests that increasing the proportion of fine particles in the suspended load also increases flow velocity and run-out distance (Brittner and Simpson, 1978; Dade and Huppert, 1995; Bursik and Woods, 1996; Simpson, 1997). Mobility of PDCs is, hence, significantly influenced by the ratio of fine to coarse particles: Douillet et al. (2013a, 2013b) observed that flow-stripping processes at cliffs generated dilute PDC modes by entrainment of air and removal of coarse particles. Finally, faster and farther reaching PDCs increase the potential threat to populated areas (Formenti and Druitt, 2003).

Particle interactions in the form of collisions have been reported for dense gas-fluidized beds (Goldschmidt et al., 2001), volcanic multiphase flows (Dobran, 2001), flows in general with pumice fragments (Sparks et al., 1997) and within volcanic conduits (Kaminski and Jaupart, 1998; Dufek and Bergantz, 2005). Abrasion of particles has been reported for ground-hugging PDCs, e.g. originating from column or dome collapse (Wohletz et al., 1989; Calder et al., 1999, 2000; Allen, 2001; Taddeucci and Palladino, 2002) and further been described through crystal-scale measurements: Freundt and Schmincke (1992) used various amounts of glass adhering to crystals in non-welded Laacher See (Eifel Volcanic Field, West Germany) PDC deposits as a measure for abrasion during transport. Relative sizes of glass rims coating crystals in matrix ash of PDCs were used as a semi-quantitative measure of ash grain abrasion. Median abrasion indices (area crystal/area glass rim) show stronger abrasion of particles in PDCs than in fall deposits. Due to the complexity of particle interactions within a highly energetic environment such as a PDC, we took the approach of analyzing a range of less complex comminution processes in order to identify those that control the generation of fine ash. This study investigated comminution through pumice collision, grinding and abrasion, together with combinations of these, in order to isolate the influence of pumice shear and compression on ash generation. Particle size distributions (PSDs) produced by normal (e.g. collision) or shear stress (e.g. abrasion) were determined in order to provide understanding of how particular mechanisms were responsible for the generation of certain size ranges of pyroclasts, such as fine ash.

Previous work

Cagnoli and Manga (2003) projected pumice cylinders onto a flat pumice bed while varying the impact angle. Kinetic energy was dissipated through frictional heat generation, particle deformation, solid electrification, surface erosion and particle breakage. The latter two parameters must be related and produced fine ash particles. The impact angle influenced the energy loss, which in turn affected generation of fine ash. These findings demonstrate that comminution is composed of a family of processes.

Fine-grained particles act to increase the mobility of granular flows, but the conversion of horizontal translational momentum into vertical fluctuation momentum by particle impacts also increases flow mobility; the vertical momentum prevents particles from interlocking frictionally (Iverson, 1997). Schwarzkopf et al. (2007) performed fall experiments (particles were dropped in a sealed container at different temperatures) and found a temperature dependent particle size distribution: an increase in temperature (max. 800 °C) decreased the resulting peak grain sizes and reduced quality of sorting. Collision experiments are also carried out in material sciences and show similar results to volcanic experiments: Salman et al. (2002) described a relation between decreasing fragmentation rate and decreasing impact velocity, angle and particle size of spherical aluminum oxide particles projected against a target. Also Hooper (2012) produced fragments by collision down to a size of 44 μm by projecting brittle, cold pressed aluminum reactive materials on thin steel plates. An increase in impact velocity increased the resulting number of fine particles.

The particular comminution process of abrasion is described in a number of studies. Kueppers et al. (2012) described the potential of clast interaction within PDCs altering the initial grain size distribution. By using a rotating chamber, situations close to basal parts of dense PDCs were mimicked with clasts interacting with each other by impact and friction. Experimental production of ash in the tumbler was dependent on clast density, porosity, initial grain size and experiment duration. Ash production rate was positively correlated with surface roughness, i.e., greater surface roughness (commonly at the start of the experiments) leads to a large ash production rate with a non-linear decay of ash production rate with time. Most ash was generally generated within the first minutes of experiments and with clasts showing low density, high porosity and an initial coarse grain size. Gee and Nimishakavi (2011) applied frictional forces to WC (tungsten carbide) through scratch tests. They observed stepwise wear during the experiments, which means that before reaching an eventual failure of the grain, it undergoes plastic deformation until a critical value of strain rate is accumulated. Similar to Kueppers et al. (2012), the experimental results show strong dependence on experiment duration, particularly the total amount of fragments produced. Maximum fracturing rate, however, is not at the beginning of the experiment but at a later stage as a critical value of plastic deformation has to be overcome.

Abrasion in a more general way can also be described by the sphericity of samples: the more a comminuting particle undergoes frictional and impacting forces, the rounder it will become. Abrading a cube to a sphere with the same diameter means a loss of 48% of the initial volume – volume that will then be mainly existent e.g. as ash particles in case of pyroclast abrasion. Spieler et al. (2003) described dacite particles following fragmentation during an experimental decompression that are often angular, whereas particles in PDC deposits are often rounded. Dufek and Manga (2008) described a clear relation between the degree of rounding and flow dynamics, while Manga et al. (2011) used the shape of pumice particles as evidence for abrasion processes within PDCs. They compared (experimentally) reworked volcanic deposits with non-reworked ones. A clear decrease in roughness and shape complexity is described for the reworked samples. The experiment can serve as an analogue to volcanic fall deposits (non-reworked) and PDC deposits (reworked). Walker (1981), who analyzed Mount St. Helens deposits, previously described this behavior.