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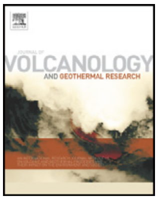

Relating the physical properties of volcanic rocks to the characteristics of ash generated by experimental abrasion

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ABSTRACT

Interactions between clasts in pyroclastic density currents (PDCs) generate volcanic ash that can be dispersed to the atmosphere in co-PDC plumes, and due to its small size, is far-travelled. We designed a series of experiments to determine the effects of pyroclast vesicularity and crystal content on the efficiency and type of ash generated by abrasion. Two different pyroclastic materials were used: (1) basaltic-andesite pyroclasts from Fuego volcano (Guatemala) with ~26–46% vesicularity and high groundmass crystallinity and (2) tephri-phonolite Avellino pumice (Vesuvius, Italy) with ~55–75% vesicularity and low groundmass crystallinity.

When milled, both clast types produced bimodal grain size distributions with fine ash modes between 4 and 5φ (32–63 μm). Although the vesicular Avellino pumice typically generated more ash than the denser Fuego pyroclasts, the ash-generating potential of a single pyroclast was independent of density, and instead governed by heterogeneous crystal and vesicle textures. One consequence of these heterogeneities was to cause the vesicular Avellino clasts to split in addition to abrading, which further enhanced abrasion efficiency. The matrix characteristics also affected ash shape and componentry, which will influence the elutriation and transport properties of ash in the atmosphere. The experimental abrasion successfully replicated some of the characteristics of natural co-PDC ash samples, as shown by similarities in the Adherence Factor, which measures the proportion of attached matrix on phenocrysts, of both the experimentally generated ash and natural co-PDC ash samples. Our results support previous studies, which have shown that abrasion is an effective mechanism for generating fine ash that is similar in size (~5φ; 30 μm) to that found in co-PDC deposits. We further show that both the abundance and nature (shape, density, components, size distribution) of those ash particles are strongly controlled by the matrix properties of the abraded pyroclasts.

1. Introduction

Efficient fragmentation of bubbly melt into a dispersion of gas and pyroclasts can generate a large proportion of volcanic ash (Walker, 1981). Most commonly, the process is fuelled by magma overpressure, which generates the explosivity that transforms magma into pyroclasts, often with fractal size distributions (Rust and Cashman, 2011; Turcotte, 1986). Ash can also form, however, by 'secondary fragmentation' (Gonnermann, 2015) within the volcanic conduit (Dufek et al., 2012; Jones et al., 2016), in the thrust region of a volcanic plume (Cioni et al., 2014) or during transport in pyroclastic density currents (PDCs; Dufek and Manga, 2008; Eychenne et al., 2012).

Here we focus on secondary fragmentation in PDCs, where the energetic flow of gas and rock facilitates abrasion and comminution between clasts, as evidenced by the abundance of rounded pumice clasts in PDC deposits (e.g. Manga et al., 2011). These processes generate fine ash, which is important because it affects PDC runout (Dufek and Manga, 2008) and can become buoyant and form a co-PDC plume that disperses the fine fraction into the atmosphere (Engwell et al., 2016; Sparks et al., 1997). These ash particles are hazardous for human health and aviation (Gudmundsson et al., 2012; Horwell, 2007), and can add substantially to the fine ash fraction of the grain size distribution created by primary fragmentation; for this reason, it is important to anticipate the contribution of ash generated in PDCs to the total ash budget produced by an eruption. Previous studies show that the amount of ash generated by abrasion in PDCs will depend on a variety of factors such as the material in the PDC, the flow conditions and background eruptive behaviour (e.g., Gravina et al., 2004; Kueppers et al., 2012; Manga et al., 2011). Here we analyse the effects of pyroclast vesicularity and crystal content on the efficiency and type of ash generated by abrasion. We take an experimental approach, following previous studies that imitate abrasion in PDCs (Kueppers et al., 2012; Manga et al., 2011; Mueller et al., 2015). We extend these studies by using variably crystalline starting material and by quantifying the amount of ash generated, as well as the ash size, componentry and shape, as these parameters influence

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the particle settling behaviour and therefore both elutriation and transport potential in the atmosphere (Coltelli et al., 2008).

2. Background

Secondary fragmentation in PDCs has the potential to alter the total grain size distribution (TGSD) of an eruption (Rose and Durant, 2009). Specifically, the small mean grain size of co-PDC ash (typically <63 μm; Engwell and Eychenne, 2016; Marti et al., 2016) increases the power law exponent of the grain size distribution (Jones et al., 2016). These small ash particles can travel long distances in the atmosphere (Engwell et al., 2014), such that co-PDC ash is often the furthest travelled ash from large ignimbrite-forming eruptions (Engwell and Eychenne, 2016). Consequently, understanding ash formation by secondary processes, such as abrasion in PDCs, is key for predicting the ash size distribution and ash dispersion potential of future PDC-generating eruptions.

The typically smooth shapes of pumice clasts in PDCs, regardless of distance of transport, indicate that clast rounding and, by inference, peak ash production, are rapid and take place close to the vent (Manga et al., 2011). Experiments have replicated the rounding of pumice clasts observed in PDC deposits and the change in clast shape during abrasion has been related to the amount of ash generated in the flow (Dufek and Manga, 2008; Manga et al., 2011). Importantly, these experiments found that the maximum extent of clast rounding is not simply a function of the mass removed by abrasion. In fact, peak clast rounding can occur when clasts have lost between 15% and 60% of their initial mass. The broad range in the mass loss indicates that the peak ash production must be related, to some extent, to the properties of the abrading material.

The effect of clast vesicularity on the efficiency of ash generation has also been examined experimentally (Kueppers et al., 2012; Mueller et al., 2015), with low-density (vesicular) clasts generating more ash than denser (less vesicular) clasts when subjected to the same duration of milling in a rock tumbler. Here we suggest, however, that the differences in ash production are controlled not only by differences in vesicularity, but also by the crystal content (size, shape and abundance of phenocrysts and microlites). As PDC components from different volcanoes are extremely varied in both vesicularity and crystal content, both properties must be assessed to anticipate the ash-generating potential of a specific PDC.

Experiments have shown that the shape of ash is also altered by abrasion (Jones et al., 2016). In an experimental study using a ball mill, Jones et al. (2016) found that increased milling duration produced ash particles with higher axial ratios (more equant shapes), which indicates the progressive rounding of ash grains, as well as increased removal of matrix from phenocrysts and phenocryst fragments (Freundt and Schmincke, 1992; Jones et al., 2016). From this perspective, it is possible that the shape and internal texture of ash generated by abrasion could be used to distinguish it from ash generated by the primary fragmentation of the magma. Field studies of the Latera Volcanic Complex, Italy, have shown that sanidine crystals in the PDC deposit have fewer boundary irregularities than crystals of the same grain size in the fall deposit (Taddeucci and Palladino, 2002). Similarly, a preliminary assessment by Liu et al. (2015a) of Tambora ash suggests that co-PDC ash particles have grain boundaries with reduced roughness compared to fall-deposit ash of the same grain size.

The phenocryst content should also affect the efficiency of ash generation by abrasion, as crystals can influence fracture and breakage patterns in pyroclasts (Wawersik and Fairhurst, 1970). However, the effect of phenocrysts is not clear. Crystals may either resist erosional processes such as abrasion in mass flows, or conversely, may introduce planes of weakness, especially if they have platy textures or have been fractured by the initial brittle fragmentation (Bindeman, 2005; Thomson et al., 2013). For instance, experiments show that crystal-rich pyroclasts from Mount Unzen are more resistant to abrasion than less crystalline samples (Kueppers et al., 2012). Similarly, crystal-bearing Medicine Lake pumice abraded more slowly than crystal-free, texturally homogenous Taupo pumice of similar density (Manga et al., 2011). What still is unclear, however, is the effect of a heterogenous distribution of phenocrysts and microlites, such as localised dense zones within a pumice clast, on the characteristics of ash generated by abrasion.

Also unexplored is the effect of groundmass crystallinity (i.e. microlite content) on the resistance of pyroclasts to abrasion. Hydrous mafic (basalt, basaltic andesite) magmas, in particular, experience extensive groundmass crystallization during rapid magma ascent in the conduit (e.g., Shea and Hammer, 2013). The products of these eruptions also have total grain size distributions (TGSDs) with less fine ash than their microlite-free counterparts (Durant and Rose, 2009; Jones et al., 2016; Rust and Cashman, 2011; Turcotte, 1986), which suggests that microlites affect primary fragmentation. We expect the role of groundmass crystallinity in secondary fragmentation processes to be four-fold. First, microlite-rich samples also have low vesicularities, which would suggest that they should resist abrasion. Second, these samples have thick bubble walls, so that even if they abrade, the ash particles should be larger than in low crystallinity, high vesicularity samples. Third, analogue and numerical experiments (Oppenheimer et al., 2015; Parmigiani et al., 2016; Parmigiani et al., 2011) show that groundmass crystals aid formation of gas pathways, which could control patterns of breakage. Finally, the crystal content of the resultant ash influences ash shape, as crystalline ash is typically blocky and lacks the perimeter concavities caused by abundant vesicles (Liu et al., 2015a, 2015b).

In this study, we test the efficiency of secondary ash generation by abrasion as a function of both vesicularity and crystallinity (phenocrysts and groundmass) of starting pyroclasts. We use samples from a violent Strombolian eruption of basaltic andesite Volcan Fuego, Guatemala, and from the Plinian Avellino eruption of tephra-phonolite from Vesuvius volcano, Italy. Informed by previous studies (Kueppers et al., 2012; Manga et al., 2011) we expected that the low density (high vesicularity) Avellino pumice would generate more ash than the high density (low vesicularity) Fuego pyroclasts. To test this hypothesis, we characterised the size, shape, vesicularity and crystallinity of the products both prior to and following abrasion experiments to dissect the links between the crystallinity, ash generation and ash shape. We then compare experimental and natural ash particles to assess the reliability of ash shape as an indicator of fragmentation process.

2.1. Volcan de Fuego (2012 eruption)

Volcan de Fuego is a stratovolcano located along the Central American volcanic arc in Guatemala. It produces frequent discrete violent Strombolian blasts with small ash plumes (<10 km) and lava flows. Occasional 'paroxysms' of heightened activity generate Vulcanian to sub Plinian eruption columns and PDCs (Rose et al., 2008). The material used in our experiments is from a paroxysmal eruption in September 2012, which was more explosive than typical Strombolian activity (Chigna et al., 2012). The eruption produced a block and ash flow that we sampled ~6 km from the vent on a field campaign in March 2016. The deposit is massive, poorly sorted and contains large blocks of basaltic andesite. We assume that the material is geochemically similar to basaltic-andesite explosive products from the 1974 eruption of Fuego (Chesner and Rose, 1984) as no geochemical analyses have been carried out on the 2012 eruptive products. This assumption is supported by the similarity of the phase assemblage to the 1974 material, and the lack of compositional differences between magma erupted in 1974, 1999 and 2003 (Berlo et al., 2012). Major element analyses of the 1974 pyroclasts show an average silica content of 56.5 wt% and a total alkali content ($Na_2O + K_2O$) of ~5.6 wt% (Chesner and Rose, 1984).

Additional material from Volcan de Fuego used in this study includes 2012 ash that was sampled from the top of a small block and ash flow. The ash represents the dilute portion of the PDC that settled out after the emplacement of the dense basal layer and is termed "PDC-surge"