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The volcanic ash problem

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Abstract

Explosive volcanic eruptions are the result of intensive magma and rock fragmentation, and they produce volcanic ash, which consists of fragments <2 mm in average diameter. The problem with volcanic ash is that its formation is poorly understood from the standpoint of eruption energetics. Because the source of explosive eruption energy should be the thermal energy of magma, and because an explosion requires rapid conversion of energy into a mechanical form, and because of the physical properties of magma thermal energy is dominantly released by conduction, the energy release on a short time scale (explosion) in volcanic processes has to be the result of a special mechanism, probably a positive feedback mechanism of fragmentation and heat exchange. In fact, the most explosive volcanic explosions are characterized by the most intensive fragmentation. In any fragmentation mechanism the generated particle sizes reflect the kinetic energy available (i.e. the fragmentation energy density). Consequently, fine ash (≤ 64 μm) provides information on fragmentation mechanisms that are the most energetic and related to the highest explosive energy release. In this letter we discuss mechanisms of formation of fine volcanic ash, using experimental results, theoretical considerations, and field observations. We focus on the potency of these mechanisms to explain fine ash produced by explosive volcanism. We conclude that quantitative analysis of fine ash particles is necessary to estimate the mechanical energy of volcanic explosions.

Keywords: explosive volcanism; volcanic hazards; tephrogenesis; energy release

Tephra is a general term for all particles produced during volcanic eruptions by mechanical fragmentation of magma and/or country rock, and volcanic ashes are those particles with average diameters <2 mm. Fine ash consists of particles <64 μm in average diameter. To many volcanologists the importance of fine ash has been restricted to phreatomagmatic (hydromagmatic) eruptions that typically produce fine ash deposits (Fig. 1) by a fragmentation mechanism involving vaporization of external water by the magmatic heat (Wohletz, 1983). In that light fine ash signified abundant water involved in the eruption. However, fine ash is also found in deposits from Plinian (magmatic) eruptions where fragmenta-

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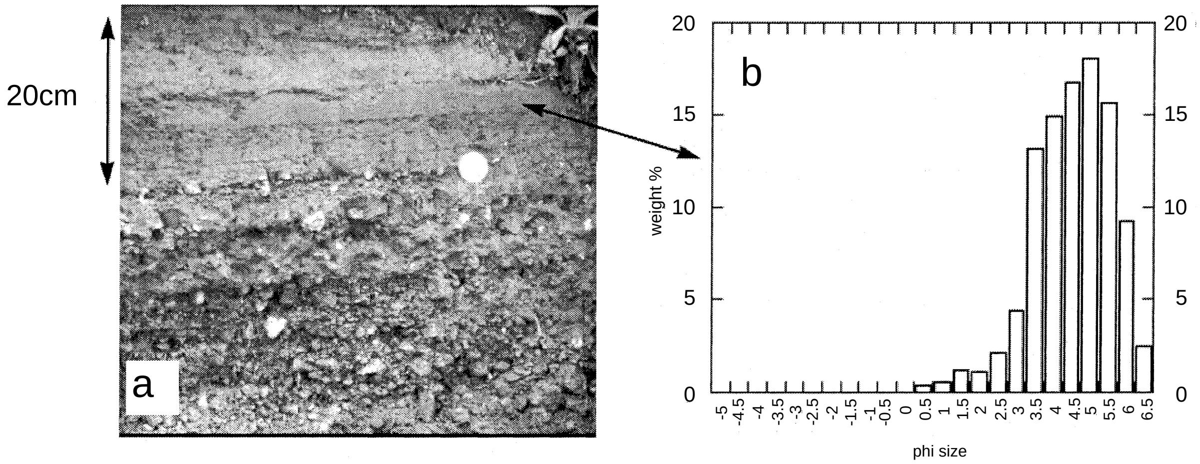

Fig. 1. (a) Fine ash layer (arrow) of phreatomagmatic origin from the Agnano Monte Spina deposits at the Phlegraean Fields (Italy). (b) Grain size distribution of the fine ash layer (phi = $-\log_2$ (diameter in mm)).

tion involves exsolution of water vapor from the magma. We now recognize that even these magmatic eruptions can produce significant proportions ($>40\%$) of fine ash (Fig. 2). In this light, fine ash signifies something more than just the eruption environment, and as we discuss below, it bears the signature of the rapidity of energy release during eruptive fragmentation. Furthermore, because the presence of fine ash suspended in the atmosphere after recent eruptions has caused severe problems to aircraft and leads to pulmonary disease in animals, fine ash has additional importance for volcanic hazard assessments.

The problem of volcanic ash we discuss concerns the energy required for its formation. Fragmentation energy is ultimately derived from the magma's internal (thermal) energy. In order to make the thermal energy available for conversion to mechanical energy via a working fluid (i.e. an expanding gas), heat must be transferred. Because heat transfer is dominated by the surface area of the magma (mostly conductive), the energy transfer rate increases with the increased surface area

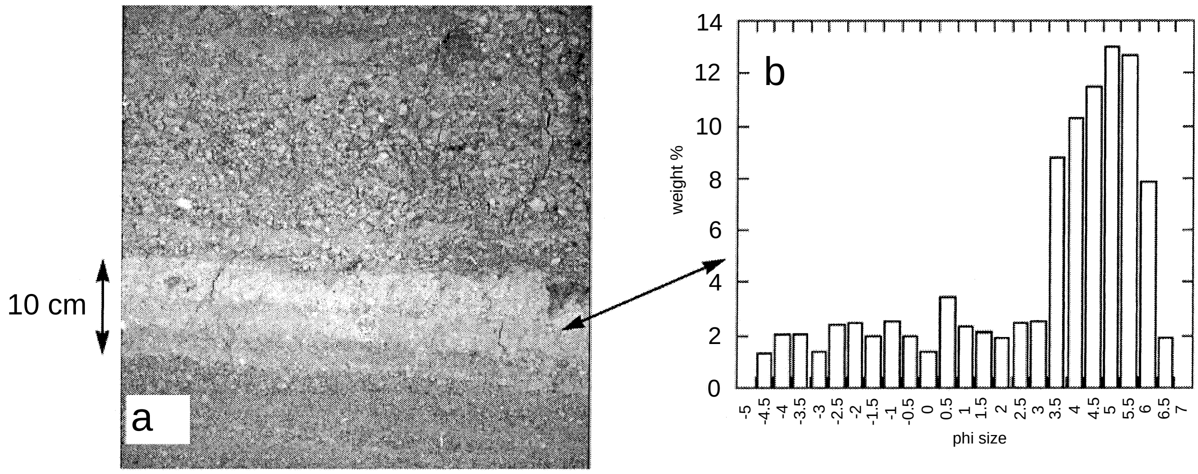

Fig. 2. (a) Fine ash layer (arrow) of magmatic origin associated to a Plinian pumice deposit of Arenal Volcano (Costa Rica). (b) Grain size distribution of the fine ash layer.

produced by fragmentation. With increasing fragmentation, volcanic ash becomes finer, and an increasing proportion of magma's thermal energy may be converted to mechanical energy in short time spans (Wohletz, 1983). Therefore, fine ash represents the product of the most energetic (highest energy transfer rate) fragmentation and eruption mechanisms. The high surface area created by fine fragmentation results in a high *explosive energy density*. Below we show that production of fine ash (hence high-energy fragmentation) likely requires a specific mechanism for fragmentation.

Natural silicate melts (magmas) are Non-Newtonian, high temperature, multi-phase, and multicomponent fluids, displaying both viscous and elastic behaviors depending upon deformation (strain) rate (Webb and Dingwell, 1990). Although various fragmentation mechanisms have been proposed for the formation of volcanic ash (Wohletz, 1983; Sparks, 1978), the mechanical fragmentation of magma can be generally viewed as taking place in two fragmentation regimes, depending upon whether the characteristic deformation times are greater or less than the viscous relaxation time (Navon et al., 1998): (1) hydrodynamic fragmentation in the ductile regime (i.e. liquid-like); and (2) brittle fragmentation in the brittle regime (i.e. solid-like).

Hydrodynamic fragmentation (1) generally involves the rapid acceleration of magma by a pressurized fluid/gas. It is restricted to deformation of 2-D interfacial areas (boundaries between the melt and gas) and is most efficient in accelerated systems at low viscosities, low interfacial tension, and high density contrast with the accelerating fluid and surrounding media. On the other hand, brittle fragmentation (2) is the result of 3-D crack growth caused by excess strain that exceeds the elastic properties of a medium (e.g. bulk modulus). Fig. 3 illustrates the general dependencies between fragmentation energy and fragment size for (I) and (II). Whereas in (I) the fragmentation energy for the generation of finer particles shows an exponential growth behavior, in (II) this dependency is more or less linear. This growth behavior is significant for the production of fine particles. For hydrodynamic fragmentation the required accelerations grow extremely high as fragmentation reaches the sizes of fine ash. However, brittle fragmentation can produce fine particles with a steady increase of strain. Let us explore these relationships a bit more quantitatively.

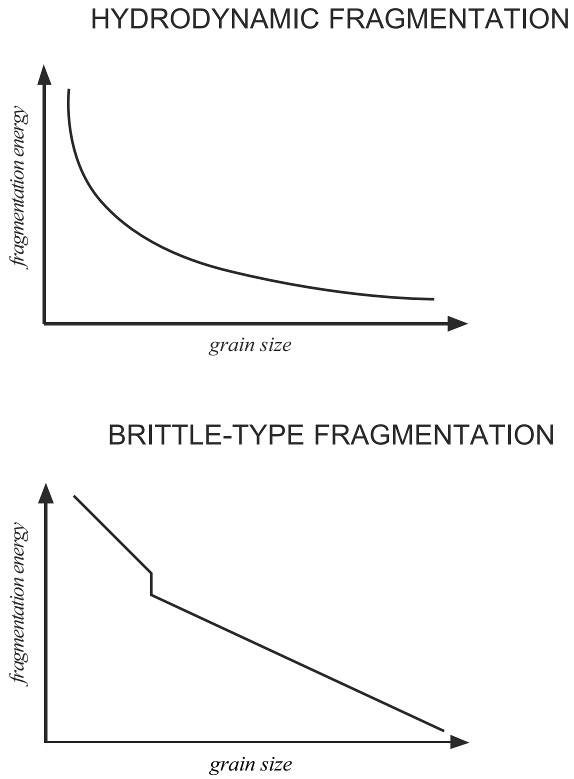

Fig. 3. Fragmentation energy vs. grain size for hydrodynamic and brittle-type mechanisms. A steady and exponential growth of the fragmentation energy for Newtonian liquids contrasts the linear growth for solids. Influences of the fabric may cause shifts in the latter case, e.g. once the grain size approaches the size of crystals in a rock or the size of polymers in a molecular fabric.

The efficacy of hydrodynamic fragmentation of magma to produce fine ash can be evaluated with the use of well established theories for hydrodynamic instabilities (Chandrasekhar, 1968; Corradini, 1981). Assuming that magma is accelerated by an expanding (pressurized) gas phase in a volcanic conduit (i.e. confined geometry), the system becomes Rayleigh–Taylor unstable, which leads to hydrodynamic fragmentation. Considering this instability for an idealized system of zero-viscosity, Newtonian fluids, a minimum fragment size can be estimated from the following relationship

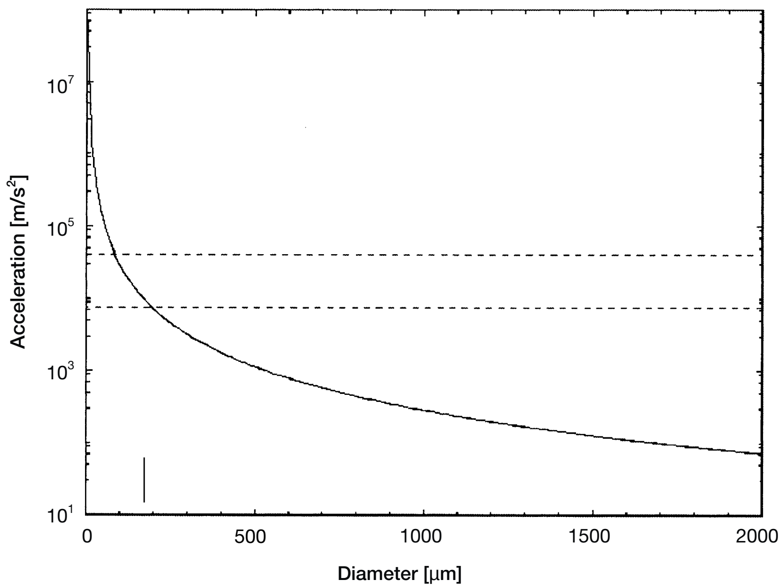

Fig. 4. Results of the calculations of efficacy of an idealized magmatic liquid (zero viscosity, Newtonian behavior). The acceleration of the liquid–gas interface is plotted vs. the grain size. The stippled lines show the range of the experimentally determined transition from hydrodynamic to brittle-type fragmentation, which corresponds to the division between coarse and fine ash.

between minimum fragment diameter D and interface acceleration a:

$$D = \left(\frac{2}{3}\right)^{3/2}\pi\left[\frac{\sigma}{a(\rho_{\text{melt}} - \rho_{\text{gas}})}\right]^{1/2}$$

Using values typical of magmatic melts for which the melt density (ρ_{melt}) is 2800 kg/m^3; the density of driving gas phase (ρ_{gas}) is 260 kg/m^3; and the interfacial tension between the melt and gas (σ) is 0.26 N/m, results shown in Fig. 4 demonstrate the relationship of minimum fragment diameter and interface acceleration. Although this estimation does not consider the effects of viscosity, solutions for the Raleigh–Taylor instability suggest that with increasing viscosity higher interface accelerations are required to promote growth of this instability. We also note that certain higher density metal constituents of magmas segregate from the melt prior to fragmentation and may have exceedingly low viscosities such that low accelerations can produce particles <10 μm in diameter (Wohletz and McQueen, 1984), but these constitute only a fraction of a wt% of most magmas. Because the interfacial acceleration is a measure of fragmentation energy and that magmas are viscous fluids, the energy required to develop fine ash by hydrodynamic fragmentation will be distinctly higher.

In contrast to hydrodynamic fragmentation mechanisms no generally accepted theory exists for the case of brittle fragmentation. Consequently, we experimentally determine the efficacy of brittle fragmentation to produce fine ash. Using a modified shock-tube set-up (Zimanowski et al., 1997), we accelerate a low viscosity ($\sim$1 Pa s) volcanic rock melt as magma simulant in a confined geometry by pressurized volume of inert gas (argon). By the use of slightly hydrated volcanic rock samples, we can produce porous samples up to 15 vol% homogeneously distributed gas bubble content. Experimental analysis consists of fragment characterization and direct physical measurements, using pressure and force transducers and highspeed cinematography. From these data we can determine the transition from ductile to brittle behavior during the melt fragmentation as a function of driving gas pressure, which is directly related to melt acceleration. This ductile-brittle transition occurs over a small range of effective accelerations as shown in Fig. 4, which displays this range with a curve calculated for the idealized hydrodynamic fragmentation model. The transition indicates that particles finer than 100–200 μm are likely the result of brittle fragmentation. The presence of gas bubbles in the system, up to 15 vol%, did not show a significant influence on the fragmentation behavior. Furthermore, these results indicate that even if idealized conditions are assumed, production of ash fragments <100 μm by hydrodynamic fragmentation requires unrealistically high interfacial accelerations of $>30\,000$ m/s^2 (~ 3000 g); hence the hydrodynamic fragmentation does not seem to adequately predict formation of a significant proportion of fine ash. In contrast, our experiments indicate that when fine ash is formed, it does so by a brittle fragmentation mechanism (Büttner et al., 1999).

Because fine ash has a relatively high surface area to mass ratio, its production requires a relatively high fragmentation energy density that might be correlated to a relatively high eruption energy. If the fine ash particles represent the *finger print* of a brittle fragmentation, as our experiments suggest, a quantitative analysis of these particles in combination with standardized laboratory experiments provides insight into the energy release rate of volcanic explosions. Our calculations and experiments indicate that fine ash is the result of fragmentation energies 50 to over 1000 times greater than that involved with formation of most coarse ash (64–2000 μm). The proportion of fine ash erupted (e.g. from a Plinian eruption), even if its volume is relatively small in comparison to coarse ash and pumice, may represent a significant part of the explosion energy release. In this sense these particles are in fact an important key to understanding explosive volcanism. A challenge to the volcanologist is to be able to evaluate the proportion of fine ash, recognizing that much of it is carried far away from the volcano in atmospheric suspension and not fully represented in the tephra deposits surrounding a volcano. A challenge for numerical modelers is to incorporate conservation equations that express the energy partitioning involved in fragmentation and formation of fine ash.

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