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PERSPECTIVES

Magma fragmentation: a perspective on emerging topics and future directions

Thomas J. Jones[1] · Katharine V. Cashman[2] · Emma J. Liu[3] · Alison C. Rust[2] · Bettina Scheu[4]

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Abstract
The breaking apart of magma into fragments is intimately related to the eruptive style and thus the nature and footprint of volcanic hazards. The size and shape distributions of the fragments, in turn, affect the efficiency of heat transfer within pyroclastic plumes and currents and the settling velocity, and so the residence time, of particles in the atmosphere. Fundamental work relating the glass transition to the fragmentation of magmas remains at the heart of conceptual and numerical models of volcanic eruptions. Current fragmentation criteria, however, do not predict the sizes and shapes of the resulting fragments, or fully account for the multiphase nature of magmas or ways in which magma can break in a fluidal manner or by thermal stress. The pulsatory, non-steady state nature of some eruptions, and related interactions with these fragmentation criteria, also requires further investigation. Here, we briefly review some recent advances in the field of magma fragmentation and provide a perspective on how integrated field, experimental and numerical modelling studies can address key outstanding challenges.

Keywords Pyroclast · Tephra · Glass transition · Thermal granulation · Inertial fragmentation · Hydrovolcanic

Introduction

The fragmentation of melts and magmas is one of the most fundamental topics in volcanology. The conditions under which high-temperature melts and multiphase magmas fragment control the eruptive style (effusive versus explosive), while the extent of fragmentation determines the eruption type (e.g. Hawaiian versus Plinian) and, ultimately, the hazard footprint. Previous reviews (Wohletz et al. 2013; Cashman and Scheu 2015; Gonnermann 2015; Zimanowski et al. 2015) summarise comprehensively the decades of work on magma fragmentation and explosive magma-water interaction. For this reason, we do not replicate these reviews but instead provide our own perspectives on several emerging topics, particularly those where recent observations or technological advances raise new lines of investigation.

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This paper constitutes part of a topical collection:

Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

✉ Thomas J. Jones
thomas.jones@liverpool.ac.uk

1 Department of Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool, UK

2 School of Earth Sciences, University of Bristol, Bristol, UK

3 Department of Earth Sciences, University College London, London, UK

4 Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität München, Munich, Germany

Fragmenting magma as a multiphase material

Primary fragmentation during explosive magmatic eruptions of all styles and magma compositions involves the breaking apart of a multiphase magma composed of melt, bubbles and, in many cases, also crystals. In low-crystallinity basalt, bubbles expand readily in response to decompression and the resulting pyroclasts are generally much larger than the predominant bubble sizes (Porritt et al. 2012; Holt et al. 2019). In higher viscosity silicic magmas, resistance to bubble expansion can increase bubble overpressure and, if gas escape by permeable flow is insufficient, overpressurised bubbles can

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force the magma apart. For this reason, tephra produced by silicic Plinian eruptions contain abundant pumiceous clasts and fine glassy ash composed of bubble wall remnants (Rust and Cashman 2011). A corollary is that permeability heterogeneities may modulate particle size distributions when fragmentation is driven by gas overpressure. Substantial progress has been made in understanding porosity–permeability hysteresis in vesiculating versus outgassing magma (Rust and Cashman 2004; Gonnermann et al. 2017), the evolution of pore connectivity (Colombier et al. 2017) and the role of decompression-induced crystallisation in modifying degassing efficiency during vesiculation (Lindoo et al. 2017; Colombier et al. 2020). However, permeable networks are not homogeneously distributed at either small (Wright and Weinberg 2009) or large scale, for example, in pumice populations containing both near-spherical and elongate vesicles. The conduit-scale models used to explain permeability variations invoke horizontal velocity gradients (Ohashi et al. 2021) but cannot explain observed sample-scale heterogeneities.

Crystals can affect fragmentation both indirectly through their influence on bubble nucleation, expansion and coalescence, and directly by localising stress and modulating magma rheology and mechanical properties (Shea 2017; Cáceres et al. 2020). Groundmass crystals may form during temporary magma arrest prior to eruption or syn-eruptively if growth rates are sufficiently high relative to decompression rates. The latter is most likely in hydrous mafic magmas where high diffusivities (relative to more silicic magmas) allow rapid crystallisation, as illustrated by observed relationships between ascent rate and groundmass crystallinity (Wright et al. 2012; Preece et al. 2016). Recent experiments and numerical models (Moitra et al. 2018; Arzilli et al. 2019) show that rapid microlite crystallisation (and the associated viscosity increase) driven by large undercooling is sufficient to promote efficient, fine fragmentation in basaltic Plinian eruptions and can promote transitions in eruption style (Mujin and Nakamura 2014). Even a few volume percent nanolites can increase the magma viscosity to a critical value for explosive fragmentation of mafic magma (Di Genova et al. 2020). A deeper understanding of nanolite formation during both syn-eruptive decompression and post-fragmentation cooling is required to put into context their rheological effects as well as their potential for increasing explosivity through acting as effective bubble nucleation sites (Cáceres et al. 2020). Experiments on crystal-rich silicic melt systems have documented the role of crystals in forming permeable pathways (Lindoo et al. 2017) and parameterised the brittle-ductile transition and associated fracture-induced degassing (Cordonnier et al. 2012; Wadsworth et al. 2018); the latter studies show that crystals induce brittle failure at lower stresses and strain rates than observed for crystal-free magmas and that fractures often initiate in the melt. Understanding fracture characteristics of crystal-melt mixtures is also important for modelling magma and fluid ascent in mush-dominated sub-volcanic magmatic systems and, by extension, interpretations of seismic gaps under potentially active volcanoes (Illsley-Kemp et al. 2021).

Pulsatory eruptions

Although numerical models of eruptions generally assume steady state conditions, most eruptive activity is unsteady; examples include Vulcanian and sub-Plinian eruption styles, as well as lateral blasts, mafic paroxysms and violent Strombolian activity. Eruptions can be unsteady, or pulsatory, on timescales of seconds, minutes, hours or days, with that unsteadiness manifested as oscillating column heights, intermittent column collapse or repeated explosions separated by short periods of repose. This unsteadiness may occur in response to changes in the magma transport pathway, magma textures, source pressure and vent exit conditions, for example. Although models (Ramos 1995; Melnik and Sparks 2002; Dufek and Bergantz 2005) have started to incorporate unsteady behaviour, the relationship to fragmentation remains poorly understood. Unsteady behaviour can cause fragmentation (e.g. changes in strain-rate) or, at least in part, be a consequence of changing fragmentation conditions (e.g. changes in magma texture), which manifest as pyroclasts with variable grain sizes (a measure of fragmentation efficiency; Rust and Cashman 2011) and porosities.

The frequency and repetitive nature of Vulcanian activity has made this eruption type, and related lateral blast eruptions, the target of numerous detailed studies (e.g. Druitt et al. 2002; Belousov et al. 2007; Wright et al. 2007; Clarke et al. 2015). Vulcanian activity is most common in intermediate magma compositions and is characterised by short durations (10 to 100 s of seconds) and high initial mass discharge rates. Eruptions occur when magma pressure beneath a dense plug is sufficient to overcome a fragmentation threshold; subsequent downward propagation of a decompression wave initiating fragmentation yields a range of pyroclast sizes and densities (Fig. 1). Most iconic are breadcrusted or cauliflower bombs, although additional production of abundant fine ash attests to the range of fragmentation efficiencies in this eruption type. Vulcanian eruptions may transition to sub-Plinian activity if the magma supply from below (partially) balances the rate of magma withdrawal by fragmentation. Resulting pyroclasts have higher porosities (Fig. 1) and smaller maximum clast sizes than Vulcanian eruptions; the combination of high and moderate porosity clasts for sub-Plinian pyroclasts also increases the susceptibility to secondary fragmentation within volcanic conduits.

Unsteady behaviour at mafic volcanoes produces activity described as Strombolian, violent Strombolian and

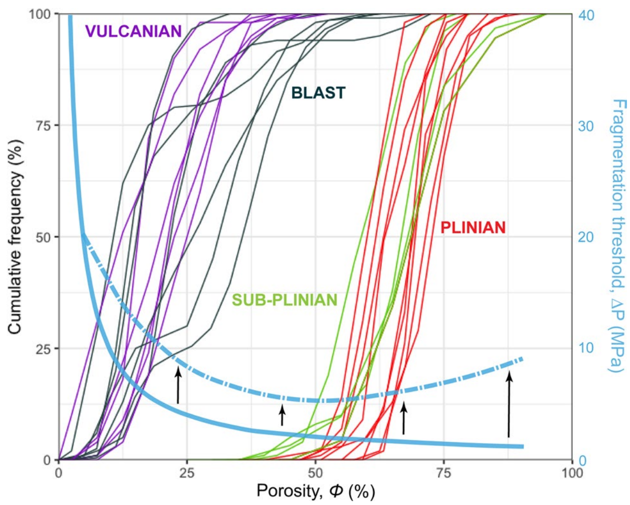

Fig. 1 Cumulative porosity distributions for silicic eruptions classified as Plinian, sub-Plinian, Vulcanian and direct blasts. Here, magma is considered silicic if the groundmass glass is $\gtrsim$ 70% SiO_2 and porosities are measured for clasts $\gtrsim$ 10 mm diameter. Also shown by the solid blue line is the fragmentation threshold (in MPa) for viscous magmas defined as $\Delta P = \sigma/\phi$, where σ is the effective tensile strength of the magma (Spieler et al. 2004; Koyaguchi et al. 2008). The dashed blue line shows how the fragmentation thresholds are increased upon increasing magma permeability (Mueller et al. 2008). Note that these thresholds apply to connected porosity while most sample measurements are reported as bulk porosity and thus represent maximum estimates of connected porosity. Sample data from Arce et al. (2005); Adams et al. (2006); Belousov et al. (2007); Mueller et al. (2011); Alfano et al. (2012); Bernard et al. (2015); Boudon et al. (2015)

paroxysmal. Small Strombolian eruptions are caused by emission of either single Taylor bubbles or bubble clusters (Taddeucci et al. 2015; Del Bello et al. 2012; Capponi et al. 2016); here, fragmentation is predominantly ductile and driven by gas expansion. Paroxysms associated with Strombolian activity show similarities to Vulcanian activity, including short energetic eruptions and fragmentation that produces a wide range of pyroclast sizes and densities (Giordano and De Astis 2021). Violent Strombolian activity is protracted, characterised by strongly oscillating eruption columns that can contain large amounts of fine ash (Fries Jr 1953) and may include simultaneous lava effusion (absence of fragmentation).

A common attribute of unsteady eruptive behaviours is a rapid change in eruption column height that may reflect variations in the conduit structure or the magma properties within the conduit. Whether individual eruptions are driven by shallow or deep processes is a point of discussion and likely varies between volcanoes and specific eruptions. Variability in constituent pyroclasts records a range of pre-eruptive decompression-driven crystallisation, vesiculation and subsequent densification and impact conditions of fragmentation. Shock tube experiments (Spieler et al. 2004) show that fragmentation conditions are intimately linked to magma porosity and permeability (Fig. 1) while tephra ejection rate is inversely related to the energy expended on fragmentation (Alatorre-Ibargüengoitia et al. 2011). The fragmentation efficiency of eruptive pulses affects the behaviour of volcanic plumes (via heat transfer efficiency). The short durations, small erupted volumes and variable grain sizes also complicate assessment of eruption parameters (magnitude, intensity) commonly used for eruption classification.

Ductile magma fragmentation

Brittle fragmentation of melts and magmas has dominated fragmentation research in the decades since the seminal work of Dingwell and Webb (1989) introduced the concept of the glass transition to volcanology. For a viscoelastic material such as silicate melt, the glass transition represents the unique temperature and deformation rate at which the mode of deformation changes from viscous to elastic. Low strain rates promote recoverable elastic deformation whereas high strain rates promote brittle failure. Specifically, this transition occurs at a critical strain-rate of $\sim 10^{-2}/\lambda_r$ where $\lambda_r = \eta_r/G$ is the structural relaxation timescale of the melt, η_r is the melt viscosity at low strain-rates and G is the shear modulus (Webb and Dingwell 1990; Papale 1999). G shows little variation across silicate melt compositions; typically, a constant value of $\approx$ 10 GPa is assumed (Dingwell and Webb 1989). For silicic melts, strain rates as low as 10^{-2} s^{-1} can be sufficient to cause brittle behaviour. However, a typical basaltic melt with a viscosity of 10^3 Pa s requires strain rates $\gtrsim 10^5$ s^{-1} to cross the glass transition and cause brittle fragmentation. Explosive basaltic eruptions do not reach the high strain rates required for brittle fragmentation, indicating that a different mechanism is causing the fragmentation of basaltic and other low viscosity melts (e.g. kimberlite, carbonatite, basanite, nephelinite) in a non-brittle, ductile manner. However, when these basaltic melts are transformed into a higher viscosity magma, by syn-eruptive crystallisation or by rapid adiabatic cooling, for example, fragmentation can occur in the brittle regime (Moitra et al. 2018; Arzilli et al. 2019; Namiki et al. 2021).

Ductile, or inertial, fragmentation is governed by fluid dynamics (Namiki and Manga 2008; Jones et al. 2019), where the magma is stretched and pulled apart in response to inertial forces (extension and shearing). Comparatively little work has been done on this fragmentation mechanism, although many parallels exist with the fundamental fluid dynamic literature (Eggers and Villermaux 2008; Pioli and Harris 2019). Shock-tube experiments on low-viscosity bubbly liquids have, however, shown that the onset of fragmentation is determined by a critical Reynolds number ~ 1 (Namiki and Manga 2008) and filament extension experiments on pure melt analogues define a critical deformation timescale that promotes fragmentation via fluid dynamic instabilities (Jones et al. 2019). Applications include fragmentation within lava fountains, splashing of spatter clasts (Sumner et al. 2005) and melt stripping from pyroclast surfaces (Moss and Russell 2011; Jones et al. 2022). Importantly, these results must now be extended to multicomponent mixtures; most promising is combining both numerical models and experimentally derived fragmentation criteria (La Spina et al. 2021).

Secondary fragmentation

Secondary fragmentation processes modify the primary grain size distributions of erupted pyroclasts; resolving these processes from that of primary fragmentation is crucial to the robust interpretation of field deposits and the definition of eruption source parameters. Size-reduction processes also have important implications for hazard assessment as finer particles have a greater surface area for heat exchange or chemical reactions, enhanced potential for triboelectric charging, longer atmospheric residence times and therefore greater dispersal distances, and are small enough to be inhaled, ingested into aircraft engines, or to disrupt ground-based infrastructure. In situ generation of fines within pyroclastic density currents (PDCs) promotes greater flow mobility and therefore extends runout distances and adds fine material to volcanic plumes.

Secondary fragmentation processes are widespread and are relevant to explosive eruptions of all magma compositions, promoting smaller grain sizes, modified grain shapes (often rounding) and increasing the fractal dimension of the grain size distribution produced (Kaminski and Jaupart 1998). These processes operate within the conduit (Dufek et al. 2012; Campbell et al. 2013), the jet region of plumes (Jones and Russell 2017), lava fountains (Jones et al. 2019; Namiki et al. 2021) and PDCs (Freundt and Schmincke 1992; Kueppers et al. 2012; Mueller et al. 2015). Proposed mechanisms for secondary fragmentation attempt to explain the roundness of particles in the PDC deposits compared to fall deposits from the same eruption (Calder et al. 2000), the bimodal grain size distributions of pyroclastic deposits from PDC-producing eruptions (Engwell and Eychenne 2016) and the abundant ash produced by lava fountaining events despite predominantly ductile fragmentation processes.

Most studies to date have focused on secondary fragmentation during large explosive eruptions, and particularly those associated with PDCs. Early experimental and numerical studies demonstrate that secondary fragmentation can reproduce many of the characteristics of natural samples and that rounding in PDCs occurs rapidly, close to the vent (Dufek and Manga 2008; Manga et al. 2011). More recent experimental studies have emphasised the importance of the starting material—size, texture and component assemblage—on secondary fragmentation mechanisms. Bubble and crystal content as well as texture influence the material properties of pyroclasts and therefore their susceptibility to secondary processes. Whilst increasing vesicularity is generally associated with more efficient size reduction and rounding, increasing crystal content can either enhance or suppress further fragmentation depending on crystal size and shape (Jones et al. 2016). Large phenocrysts can provide planes of weakness; groundmass microlites, however, increase resistance to milling and impose a lower limit to particle size (Buckland et al. 2018; Hornby et al. 2019). Heterogeneity in size and/or density in the (multi-component) starting assemblage—for example, the presence of lithic material—accelerates size-reduction processes (Bernard and Le Pennec 2016) and can be further amplified by irregular conduit geometries causing constrictions (Paredes-Mariño et al. 2019).

Secondary fragmentation processes during fountaining of low viscosity, crystal-poor mafic magmas are less well studied. Here, primary magma fragmentation is predominantly ductile and further ductile fragmentation can occur in-flight (Jones et al. 2019, 2022; Edwards et al. 2020; Thivet et al. 2020). Recent field observations and numerical models have shown, however, that under conditions of high gas flux, rapid adiabatic cooling of the exsolved gas phase can quench the surface of molten pyroclasts fast enough to prevent development of permeability (Namiki et al. 2021). Under these conditions, continued expansion can cause sequential brittle fragmentation of the originally fluidal pyroclasts, as observed during the 2018 eruption of Kīlauea, Hawai'i (Namiki et al. 2021), for example. Many parallels exist with mechanisms of turbulent shedding and disintegration by thermal stresses proposed to explain fine ash generation in mafic hydromagmatic eruptions (Mastin 2007; Liu et al. 2017).

Vesicular magma water interaction

Magma frequently interacts with water in its liquid state as ground-, hydrothermal, sea or lake water or in its solid state as glacial ice; these interactions produce a great variety of eruption styles and products. Such eruptions are termed "hydromagmatic", "hydrovolcanic" or "phreatomagmatic", with the terms often considered interchangeable, although more recently "phreatomagmatic" has been used more specifically for explosive magma-water interaction and implied a fragmentation mechanism of molten fuel coolant interaction (MCFI) (Németh and Kósik 2020). During MFCI, rapid heat transfer across the magma-water interface and the resulting vaporisation causes magma fragmentation by hydraulic forcing (Sheridan and Wohletz 1981; Wohletz 1986; Wohletz et al. 2013). Experiments to simulate MFCI have, however, mostly used single-phase low viscosity melt; resulting fragments are poorly to non-vesicular and (moderately) fine-grained due to efficient energy conversion and have been used to suggest that dense magma could erupt explosively only by external water interaction. These observations have, in turn, invited the concept that the lack of vesicularity is a diagnostic property of hydromagmatic deposits. This is not always the case and must be revisited.

Over the past decade, various studies have highlighted the importance of *vesicular* magma-water interaction for a variety of hydrovolcanic settings including Surtseyan eruptions (Colombier et al. 2019), Phreatoplinian eruptions such as the silicic Askja 1875 eruption (Carey et al. 2009) and basaltic fissure eruptions such as the Hverfjall Fires (Liu et al. 2017) and the tenth century Eldgjá eruption (Moreland et al. 2019; Hajimirza et al. 2022). In cases where simultaneous magmatic and hydromagmatic explosive activity occurs, the wet eruption products are substantially finer-grained than their dry counterparts, yet the vesicularity and bubble textures of the dry and wet phases are often comparable (Liu et al. 2017; Houghton and Carey 2019). Therefore, it is unlikely that water interaction caused primary magma fragmentation but rather modulated it to varying degrees—further fragmenting vesicular pyroclasts originally produced by decompression.

Granulation in response to thermal stresses caused by rapid cooling of the magma is an efficient mechanism for producing abundant fine particles that are either liberated into the plume or remain in place, coating their parental clasts to form accretionary lapilli (Kokelaar 1986; Liu et al. 2015; van Otterloo et al. 2015; Colombier et al. 2019). Thermal granulation has been identified as important in Surtseyan eruptions and is likely a key process during vesicular magma interaction with water (Fig. 2). Contrary to MFCI, thermal granulation may not contribute significantly to the explosivity of an eruption via volumetric expansion but can affect plume dynamics through grain size reduction. While MFCI appears key for hydrovolcanic fragmentation of dense or poorly-vesicular magma, it is arguable if, and under what conditions, it occurs during vesicular magma-water interaction.

There persists a need to untangle the interplay between purely magmatic and magma-water-driven processes, especially for variably vesicular magma, rather than pure melts. Constraining the extent to which pyroclast characteristics (e.g., grain size and texture), across the full range of size fractions, may be diagnostic of particular fragmentation mechanisms is key to the use of deposits to infer eruptive processes (White and Valentine 2016). Additionally, there is an urgent need to clarify magma-water interaction terminology, particularly the broad use of the term "phreatomagmatic" and, at the same time, the genetic association of the term and MFCI as the driving mechanism.

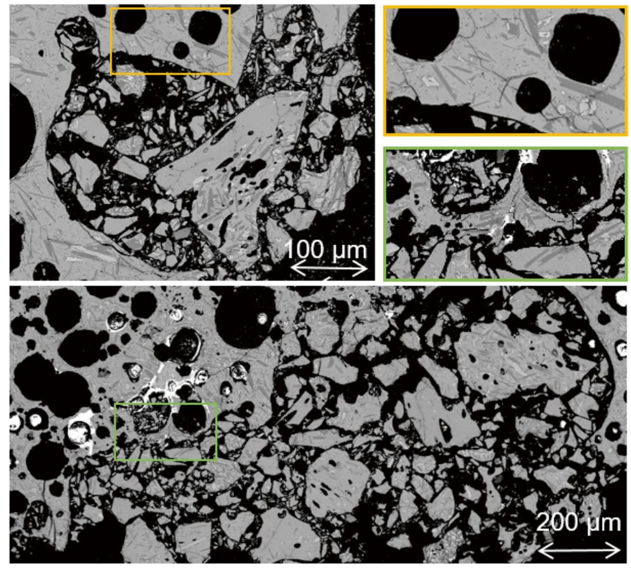

Fig. 2 Fragmentation of vesicular magma. BSE images of vesicular clasts from 2014 to 2015 Surtseayan eruption of Hunga Tonga-Hunga Ha'apai showing jigsaw-fit textures typical for thermal granulation at margins of the clasts, interacting with vesicles

Looking backward and forward

Despite decades of work on magma fragmentation with major achievements, key knowledge gaps remain, especially related to heterogeneity. The multiphase nature of magma affects fragmentation criteria (e.g. porosity-dependant thresholds; Fig. 1) and fragmentation style (e.g. brittle versus ductile or MFCI versus thermal granulation). Heterogeneities in the crystal and bubble content of magmas introduce additional complexity that may modify fragmentation processes further. Textural properties that vary between pyroclasts can affect their relative competence and, for example, their susceptibility to secondary fragmentation. Spatial variations in magma properties also occur throughout the magmatic feeding system, with an obvious example coming from the diverse pyroclast characteristics of Vulcanian eruptions that record a relatively dense and impermeable magma cap overlying variably vesicular magma (Melnik and Sparks 2002; Scheu et al. 2006; Wright et al. 2007). Spatial changes in texture and fragmentation style affect the range of model criteria appropriate for a single eruption or eruptive episode. Temporal heterogeneity introduced during magma ascent, where associated degassing, and possibly cooling, cause nano/microlite crystallisation, may further modify fragmentation style and enhance fragmentation efficiency.

In this perspective, we emphasise that the fragmentation of bubble and/or crystal bearing magmas, rather than pure melts, remains a prime target for future investigation. This is particularly true for the topics of ductile magma fragmentation and magma-water interaction, where most (experimental) work to date has focused on bubble- and crystal-free melts; there are clear research opportunities to extend experiments to more realistic, texturally heterogenous magmas. Although experiments using natural samples highlight the importance of heterogeneous material properties during secondary fragmentation, experimental results have yet to be fully incorporated into numerical models of conduit or pyroclastic flow processes. Full integration of experimental data and probabilistic numerical models would fulfil a long-term goal in volcanology and contribute to refining our interpretations of eruption deposits as indicators of eruptive (fragmentation) processes. Also fundamental are the temporal and spatial heterogeneity of magma and the common manifestation of these heterogeneities as unsteady or pulsatory eruptive behaviour. Incorporating temporal and spatial heterogeneity into both experimental studies and numerical models of unsteady eruptive activity presents a realistic goal for the next decade.

From a broader perspective, we suggest that advanced numerical models of magma ascent and eruption coupled with rapidly developing X-ray tomography techniques will substantially advance future fragmentation research. The possibility to image and measure textural and rheological changes in magma in 3D, and increasingly 4D, during deformation is especially promising (Colombier et al. 2020; Dobson et al. 2020) and will allow examination of the combined roles of deformation and magma heterogeneity on fragmentation. Additionally, our increasing ability to observe eruptive activity in real-time, using high-speed video (Taddeucci et al. 2021), sensors on unoccupied aerial systems (James et al. 2020) and advanced geophysical techniques, offers new opportunities to constrain elusive dynamic eruptive parameters (e.g. strain-rate within the conduit, differential pyroclast-gas velocity), at least for lower energy eruptions. However, challenges remain in finding ways to "reverse engineer" geophysical, geochemical and physical volcanological observations to infer conduit processes and eruption dynamics (including syn-eruptive energy balances). For example, commonly assumed diagnostic features of pyroclasts may be non-unique and forecasts of unsteady behaviour and abrupt transitions in eruption regime, although well documented, remain difficult to anticipate in real time. These challenges require improved models of fragmentation that fully account for the multiphase material properties of magma and both incorporate and inform geophysical observations of conduit processes.

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