Volcanology:
Magma behaving brittly

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Low viscosities may not preclude brittle magma fragmentation under certain conditions, according to field observations and experimental evidence that suggest the conditions for brittle fragmentation may be met in many explosive mafic eruptions.

Explosive volcanic eruptions can produce multiple hazards, including widespread dispersal of volcanic ash and pyroclastic density currents**.** Magma fragmentation generates the explosive force during eruptions and the style of fragmentation determines the nature and scale of the eruption and its hazards[1]. Brittle fragmentation is a signature of the most energetic eruptions that produce large hazard footprints. While long-associated with viscous, silica-rich magmas, a mechanistic understanding of brittle fragmentation in low-viscosity magmas remains elusive. Two studies in *Nature Geoscience* explore the fragmentation of mafic magmas and find that brittle behaviour in low-viscosity melts may be more common than previously thought, occurring prior to and following fragmentation by fluidal processes. Namiki and colleagues[2] show that rapid cooling of the outer surface of liquid clasts combined with continuing expansion of gas trapped inside the still hot interior promotes secondary brittle fragmentation within lava fountains (Figure 1). Taddeucci and colleagues[3] suggest that fracturing and healing of low viscosity melts may precede many explosive mafic eruptions.

Magma fragmentation breaks magma apart, transforming it from a continuous liquid that contains gas bubbles into a continuous gas that contains fragments of liquid magma, known as pyroclasts[1]. It can take place in either a solid (brittle) or liquid (fluidal) state and is driven by the nucleation and rapid expansion of gas bubbles as magma ascends and decompresses. Whether fragmentation is brittle or fluidal is determined by the response of the melt to applied strain from bubble expansion or shearing[1]. For a magma to break brittly, it must be deformed faster than it can relax by viscous flow; that is, the strain rate must be high enough to cause the melt to behave as a glassy solid. The transition from viscous to brittle behaviour is known as the glass transition and depends on temperature, strain rate, viscosity and melt composition[4]. Brittle fragmentation of low-viscosity mafic magmas requires exceedingly high strain rates or a rapid change in either viscosity (for example, through late-stage crystallisation)[5,6] or temperature[7]. Instead, explosive mafic fragmentation is generally fluidal, where magma is stretched and pulled apart in response to extension and shearing in lava jets and fountains[8,9].

Differences in the magma fragmentation efficiency translate into distinct hazard scenarios. Highly efficient brittle fragmentation shatters the magma into abundant fine pieces, mostly into ash of less than

2 mm. This fine-grained volcanic ash is particularly hazardous as particles have long atmospheric residence times and are small enough to be inhaled[10], or ingested into aircraft jet engines[11]. Even small lapilli (2—64 mm diameter) can be transported tens of kilometres downwind[12] where they can damage infrastructure and contaminate water supplies[13]. Finely-fragmented volcanic material can also be remobilised for months to years following the end of an eruption, thereby prolonging the hazard[14]. Fluidal fragmentation generates coarse-grained pyroclasts where the particle size is governed by the length scale of fluid instabilities[8,15]. In order for accurate assessment of the volcanic hazards to be made, a mechanistic and quantitative understanding of the interplay between fluidal and brittle fragmentation in low viscosity magmas is required, as this will govern the size distribution and dispersal of the pyroclasts.

Namiki and colleagues use infrared cameras to image the lava fountain during the 2018 Kilauea eruption. They observe pyroclasts with a characteristic size of approximately 0.3 m, as predicted by fluidal fragmentation theory. However, a subpopulation of smaller particles exhibit a fractal size distribution, a signature of brittle fragmentation[16]. They therefore conclude that both fluidal and brittle fragmentation processes are required to explain the airborne size distribution of pyroclasts.

When bubbly magma fragments fluidally, gas is liberated. Namiki and colleagues model the effect of rapid expansion on the temperature of this liberated gas. They find that adiabatic cooling of a surrounding gas phase can quench the outer surface of molten pyroclasts. If this quenched, glassy surface forms before permeability can develop, gas and volatiles are trapped within the pyroclast. As the interior of the pyroclast cools more slowly, residual volatiles—mainly water—diffuse into growing bubbles and the exterior rind can fracture and crack, causing the clast that was initially formed fluidly to disintegrate brittly. This process could repeat several times while in the fountain, generating progressively smaller fragments by sequential brittle fragmentation. Secondary fragmentation has been reported previously at Piton de la Fournaise[17], but is now explained in a quantitative theoretical framework.

Taddeucci and colleagues[3] examine the internal textures of pyroclasts from a range of mafic volcanoes and eruptive styles. They find in situ, brittly broken crystals surrounded by intact glass. Using high temperature laboratory experiments, Taddeucci and colleagues explain the isolated broken crystals by early brittle fragmentation in the shallow conduit, in response to rapid transient deformation, followed by healing of melt fractures through viscous flow. This challenges, but is not to the exclusion of, previous interpretations that attribute broken crystals to flow shear or impact breakage[18,19]. The fractures associated with this cryptic brittle fragmentation provide additional surface area for volatile diffusion out of the magma as well as efficient pathways that promote gas migration and outgassing, which affects the development of permeability and thus explosive potential. In addition, Taddeucci and colleagues[3] highlight that unhealed fractures provide planes of weakness vulnerable to later re-breaking, which may further amplify the secondary brittle fragmentation modelled by Namiki and colleagues[2].

Both of these studies[2,3] pose challenges for our current methods of hazard assessment. The brittle behaviour observed by Namiki and colleagues[2] was only seen during periods of high gas content within the fountain. As previous studies have identified a link between fountain height (a function of gas content) and the dispersal of fine-grained bubbly pyroclasts[12], this observed coupling of fragmentation mode and fountain gas content implies that the size distribution, and dispersal, of pyroclasts is dynamic and may even fluctuate during a single fountaining episode. And, if the fracture healing as described by Teddeucci and colleagues[3] is indeed pervasive, then the size distribution of erupted pyroclasts—long taken as an indicator of the energy consumed by fragmentation[16]—may not reflect the true fragmentation efficiency.

We still have some way to go before we can claim a fully quantitative understanding of the range of conditions under which these two mechanisms operate. To forecast the expected particle size distribution for mafic eruptions based on specific eruptive parameters requires further integrated field, experimental and modelling studies. These must account explicitly for the rheological properties of multiphase magmas (melt + bubbles + crystals), which are at present poorly constrained compared to more simplified single and two-phase scenarios.

Namiki et al.,[2] and Taddeucci et al.,[3] add fuel to the debate over the role of brittle fragmentation in mafic explosive eruptions. For accurate assessment of volcanic hazards associated with explosive mafic eruptions further mechanistic and quantitative understanding of brittle fragmentation in low viscosity magmas is needed but these two studies suggest that not only are the conditions for fracturing met more commonly than previously thought, sequential fragmentation may also be the norm.

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Figure 1: Magma fragmentation in the 2018 Kilauea eruption, Hawai'i. Based on observations and modelling of the 2018 Kilauea eruption, Hawaii, Namiki and colleagues[2] argue that secondary brittle processes amplify the efficiency of magma fragmentation in lava fountains under certain conditions. Taddeucci and colleagues[3] suggest that fracturing and healing of low viscosity magmas may precede many explosive mafic eruptions. Together, these studies pose challenges for hazard assessment and suggest that conditions for brittle fracturing of low-viscosity magmas may be relatively common.

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