The products of primary magma fragmentation finally revealed by pumice agglomerates

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ABSTRACT

Following rapid decompression in the conduit of a volcano, magma breaks into ash- to block-sized fragments, powering explosive sub-Plinian and Plinian eruptions that may generate destructive pyroclastic flows and falls. It is thus crucial to assess how magma breaks up into fragments. This task is difficult, however, because of the subterranean nature of the entire process and because the original size of pristine fragments is modified by secondary fragmentation and expansion. New textural observations of sub-Plinian and Plinian pumice lapilli reveal that some primary products of magma fragmentation survive by sintering together within seconds of magma break-up. Their size distributions reflect the energetics of fragmentation, consistent with products of rapid decompression experiments. Pumice aggregates thus offer a unique window into the previously inaccessible primary fragmentation process and could be used to determine the potential energy of fragmentation.

INTRODUCTION

Explosive volcanic eruptions of silicic magma result from fragmentation of magma below Earth’s surface into pyroclasts ranging in size from ash to lapilli and blocks. During magma ascent, decreasing pressure forces gas-saturated magma to nucleate bubbles of supercritical fluid. Bubbles then grow by the diffusion of volatiles from the melt and the expansion of the exsolved vapor phase, causing an increase in magma porosity, magma acceleration, and further degassing. Simultaneously, as viscous stresses in the melt impede bubble growth, vapor overpressure therein increases (Gonnermann and Manga, 2007). When bubble overpressure exceeds the tensile strength of the surrounding melt and/or if the expanding melt is subjected to a critical strain rate (Dingwell, 1996; Papale, 1999; Zhang, 1999), magma explosively fragments into pyroclasts that range from submicron (ash) to macroscopic (blocks) in size.

Full deposits from explosive Plinian eruptions of silicic magmas have a size distribution different from that expected for a single fragmentation event (Kaminski and Jaupart, 1998). The size distribution of the products of rock fragmentation invariably follows a power law, \( N = \lambda d^{-D} \), where \( N \) is the number of particles greater than size \( d \), \( \lambda \) is a scaling factor, and \( D \) is the power-law exponent (fractal dimension). For a variety of experimentally fragmented geological objects, fractal dimensions are always \(<3\) and, in most cases, in the range \( 2.5 \pm 0.3 \) (Turcotte, 1997; Kaminski and Jaupart, 1998). By contrast, full deposits of silicic Plinian eruptions have total grain-size distributions that follow a power-law distribution with fractal dimension \( D \sim 3 \) (Kaminski and Jaupart, 1998; Rust and Cashman, 2011; Pioli et al., 2019; Carazzo et al., 2020). The difference in \( D \) values between experimental and natural fragmentation products has been explained by secondary pyroclast fragmentation in response to thermal stresses during decompression and/or disruptive inter-particle collisions and abrasion in the conduit and volcanic plume (Dufek et al., 2012; Jones et al., 2017). This \( D \)-value differential is at present an unconstrained metric of secondary fragmentation; as the true size distribution of primarily fragmented pyroclasts remains unknown, so too does the degree to which secondary fragmentation impacts pyroclast size and shape distributions. However, new textural observations of sub-Plinian and Plinian lapilli reported here, interpreted in light of recent studies into the origin of obsidian pyroclasts (Gardner et al., 2017; Watkins et al., 2017), indicate that some pumice pyroclasts form by post-fragmentation amalgamation of “protopyroclasts” prior to secondary collisional processes.

METHODS

We made new textural observations of pumice lapilli from four silicic sub-Plinian and Plinian eruptions at Medicine Lake volcano (California, USA; 1060 CE Glass Mountain eruption; Heiken, 1978), Newberry volcano (Oregon, USA; 700 CE Big Obsidian Flow eruption; Kuehn, 2002), and Mount Mazama–Giiwas (Oregon; ca. 5750 BCE Cleetwood and climactic eruptions; Young, 1990; Bacon, 1983). These explosive eruptions ejected \( \sim 0.1 \) km\(^3\) (explosive phase of the Big Obsidian Flow and Glass Mountain eruptions) to \( \sim 60 \) km\(^3\) (climactic phase of the ca. 5750 BCE eruption of Mount Mazama–Giiwas) of crystal-poor rhyodacitic to rhyolitic magma. For each eruption, 100 juvenile pumice lapilli, collected from a single bed, were analyzed for their size and porosity (bulk and connected; see the Supplemental Material). In all suites, some pyroclasts exhibit distinct surficial textures from inter-clast amalgamation,
visible under stereo microscope. The proportion of these clasts was determined, and 28 variably textured lapilli, wherein six to nine (some exhibiting amalgamation-like textures, some not) were arbitrarily chosen from each suite, were then analyzed by X-ray computed tomography (CT; see the Supplemental Material).

POROSITY AND EXTERNAL TEXTURE OF THE LAPILLI SUITES

The bulk porosity and the ratio of connected to bulk porosity (connectivity) of the pyroclasts suites are roughly positively correlated (Fig. 1). Moreover, median bulk porosity and connectivity increase with erupted volume and mass discharge rate, from 72% ± 7% and 0.88 ± 0.06, respectively, for Medicine Lake, to 76% ± 4% and 0.89 ± 0.04 for Newberry, to 83% ± 4% and 0.94 ± 0.03 for the Cleetwood phase of Mazama and 87% ± 3% and 1.00 ± 0.03 for the climactic phase of the Mazama eruption. The bulk porosity and connectivity of all four suites of pyroclasts are typical of sub-Plinian and Plinian lapilli in general (Mueller et al., 2011; Colombier et al., 2017). All suites contain pumice lapilli that have surficial textural evidence of amalgamation. The presence of such textures does not depend on the size, porosity, or connectivity of the pyroclast (Fig. 1). However, the overall proportion of extremely likely to most likely amalgamated clasts (see the Supplemental Material for details) decreases with erupted volume and mass discharge rate, from 17%–37% in the Medicine Lake and 17%–39% in the Newberry suites to 14%–25% in the Cleetwood phase and 5%–19% in the climactic phase of Mazama.

IDENTIFYING PROTOPYROCLASTS

All visually amalgamated pyroclasts, and more than a third (5 of 14) of those appearing texturally homogeneous, consist of juxtaposed domains with variable porosities, vesicle sizes, and vesicle orientations when viewed under CT (Fig. 2). These domains range in size from a few microns to >1 cm. The contrast in porosity and/or vesicle sizes and orientations between textural domains is typically sharp (Figs. 2A and 2D), but more subtle differences in vesicle texture between domains exist and are trackable in three-dimensional CT scans (e.g., Figs. 2B and 2C). Single pyroclasts can contain several to thousands of discrete domains (Fig. 2). Most domains <∼30 microns are almost entirely dense (Figs. 2E and 2F). Boundaries between some larger domains form topographically bright bands a few microns to tens of microns in thickness (Figs. 2A and 2D). Scanning electron microscope (SEM) images taken at higher resolution show that these boundaries include partly sintered ash in between domains (Figs. 2E and 2F) and/or densified domain rims between which some pores are flattened (Fig. 2D). We note that in most CT scans, boundaries between domains are more easily identifiable toward the outskirts of the clast.

The new imagery allows us to quantify the size distribution of textural domains from ~3 μm up to the size of the lapilli themselves (11–31 mm). In all four cases, the size distribution of textural domains defines a power-law distribution that is best fitted using an exponent of 2.4–2.6 (Fig. 3C). Prior to amalgamation, these textural domains had a size distribution that matched that predicted by fragmentation experiments conducted on a variety of geological objects (fractal dimension of 2.5 ± 0.3; Turcotte, 1997; Kaminski and Jaupart, 1998). Porous volcanic pyroclasts, when rapidly decompressed in a shock-tube apparatus, fragment if the change in pressure exceeds a threshold of approximately σ/φ, where σ ≈ 1 MPa is the tensile strength of the silicate melt and φ is the porosity of the magma (Spieri et al., 2004). The fractal dimension of these products typically falls within a narrow range of 2.4 ± 0.2 (Alidibirov and Dingwell, 1996; Kueppers et al., 2006). We thus interpret the textural domains highlighted in Figure 2 to be protopyroclasts, the direct products of primary magmatic fragmentation in the conduit. Because their porosity and connectivity are typical of sub-Plinian and Plinian pumice lapilli (Fig. 1; Rust and Cashman, 2011; Colombier et al., 2017) and none of the 400 clasts analyzed have obsidian edges, amalgamated pyroclasts are highly unlikely to derive from tuffisitic infill. Instead, we posit that these protopyroclasts were preserved by amalgamation and partial sintering inside the conduit during and/or immediately following primary fragmentation (Fig. 4). The size distributions of silicic Plinian fallout deposits, which have a fractal dimension of 3.4 ± 0.3 (Fig. 3C; Kaminski and Jaupart, 1998; Rust and Cashman, 2011; Pioli et al., 2019; Carazzo et al., 2020), must

Figure 1. Pyroclast bulk porosity distribution (left axes) and ratio of connected to bulk porosity (i.e., connectivity; right axes) for each eruption. Circle color represents likelihood that each pyroclast is amalgamation of protopyroclasts as based on observation under stereo microscope. For clasts analyzed by X-ray computed tomography (CT) (diamonds), color indicates whether clast exhibits CT/SEM (scanning electron microscope) evidence of amalgamation. Red diamond with thicker edge corresponds to clast shown in Figure 2 for each eruption.
For protopyroclasts to amalgamate, they must collide at low-enough energies to not further break apart and stick together (Dufek et al., 2012). We posit that this occurs during the fluidization of the packed beds of pyroclasts. This is a zone between the unfragmented magma below and the fully fluidized gas-pyroclast mixture above—in other words, at or just above the fragmentation zone (Dartevelle and Valentine, 2007). In that zone, both the density of particles and their acceleration are high, but acceleration slightly differs for particles of different size, promoting low-energy collisions. As melt viscosity increases during ascent post-fragmentation due to permeable outgassing and diffusive water loss (Rust and Cashman, 2011), so too does the sintering time scale. Pyroclasts thus have the highest chance to collide, amalgamate, and partially sinter in the vicinity of the fragmentation zone. Obsidian pyroclasts from the 1340 CE North Mono eruption (Mono Craters, California) formed by cycles of fragmentation, sintering and/or suturing, and annealing and/or relaxation over varying depths on the conduit wall (Gardner et al., 2017; Watkins et al., 2017). We propose that this process also occurs inside the gas-pyroclast mixture across the conduit, wherein limited residence time during rapid final ascent limits maturation and densification of the aggregates, preserving protopyroclasts’ initial sizes and textures.

Sintering after initial amalgamation must rapidly occur between fragmentation and quench, over the course of ~10–60 s (Gardner et al., 1996). In the absence of confining pressure, the sintering time scale of randomly packed, monodisperse spherical particles is given by (Wadsworth et al., 2019):

$$\tau = \frac{\mu R}{\sigma}$$  \hspace{1cm} (1)

where $\tau$ (in seconds) is the sintering time scale, $\mu$ (in Pa·s) is the viscosity of the melt, $R$ (in meters) is the particle radius, and $\sigma$ is the surface tension. Sintering between protopyroclasts appears limited, usually occurring over length scales of ~10^{-5} m or less (Figs. 2E and 2F). Assuming disequilibrium degassing, rhyolitic melt viscosity at fragmentation is ~10^6 Pa·s (Gonnermann and Houghton, 2012; Hajimirza et al., 2021), a reasonable value for a wide range of silicic magmas (Gardner et al., 1996). For a surface tension of ~0.2 N/m (Bagdassarov et al., 2000) and in the absence of confining pressure, $R = \sim 10^{-4}$ m protopyroclasts can sinter above the fragmentation zone within ~50 s, prior to quench (Equation 1).

**IMPLICATIONS**

We examined typical pyroclasts from four sub-Plinian and Plinian eruptions that span more than three orders of magnitude of erupted ejecta by volume and more than two orders of magnitude of mass discharge rates. We postulate that syn- and/or post-fragmentation amalgamation and partial sintering of protopyroclasts in the conduit is widespread and has been previously overlooked or interpreted differently. Highly silicic pumice-fall agglomerates have been rarely reported (Newberry, Oregon, USA; Kuehn, 2002; and Santorini, Greece; Teddeucci and Wohletz, 2001), yet contiguous heterogeneous textures at the sub-millimeter scale have been widely documented in highly silicic tephra (e.g., Wright and Weinberg, 2009, their figures 1A and 4A; Schipper et al., 2013, their figure 9; Pistolesi et al., 2015, their figure 15). While they are usually interpreted as resulting from heterogeneities in material properties and/or localized degassing, these textures may be from syn- and/or post-fragmentation amalgamation and partial sintering of protopyroclasts, as described herein. Additionally, Newberry (~10^7 kg/s; Gardner et al., 1998) and Medicine Lake pyroclasts preserve these textures more often and more distinctly than do those from Mazama.
This observation could be an indication that the fluidization of packed beds of protopyroclasts at fragmentation during more explosive eruptions is more efficient, leaving less time for mixing and amalgamation of protopyroclasts with highly contrasting textures.

Magmatic fragmentation converts potential energy from the compressed gas inside bubbles into kinetic energy and surface energy of fractures in the melt (Grady, 1982). The size distribution of fragmentation products should reflect eruption explosivity, wherein the fractal dimension of the fragment size distribution increases with the potential energy for fragmentation (Kueppers et al., 2011). The two black reference lines illustrate the difference in slope between power-law distributions with fractal dimension of 2.4 and 3.0.
2006). However, the unconstrained overprint of secondary fragmentation on the final size distribution of tephras renders this task challenging. The textures described here provide a framework for quantifying the size distribution of primary magmatic fragmentation products, and so could be used to obtain the potential energy for fragmentation (Yew and Taylor, 1994; Kolzenburg et al., 2013). These textures also show that, contrary to what is claimed at this time, studies of the size and texture of the final pyroclasts (rather than individual protopyroclasts) may tell a post-rather than pre-fragmentation story.

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