Strain localization in vesicular magma: Implications for rheology and fragmentation

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ABSTRACT

The rheology of two- or three-phase magmas has been the focus of much interest because it controls magma ascent and eruption behavior. Research on magma rheology has typically considered homogeneous flow. Here we demonstrate, based on natural examples, that strain resulting from viscous flow preceding explosive fragmentation localizes into shear zones at a microscopic scale. Strain localization affects the rheological behavior of magmas, modifying predictions based on experiments. Localization leads to high-strain-rate shear zones, where elongated, sheared vesicles and shear heating have a weakening effect, surrounding regions of relatively low strain rate, where subequant vesicles have a strengthening effect. Thus, energy is dissipated more efficiently into localized bands, where strain rate increases through feedback effects and can lead to melt fragmentation.

INTRODUCTION

The destructive nature of explosive eruptions has led to intense efforts to understand brittle fragmentation of magma. In silicic melts, the ductile-brittle transition can occur as a response to strain-rate–dependent crossing of the glass transition (Dingwell and Webb, 1989). In rapidly decompressed volcanic systems, strain rates are likely to be high enough to cause brittle fragmentation (e.g., Alidibirov and Dingwell, 1996). Models have shown that strain-induced fragmentation is also possible during sustained eruptions (Papale, 1999).

Recent work has highlighted the role of shear localization and shear heating in causing a deviation from idealized, Newtonian behavior during magma ascent, leading to brittle behavior and earlier fragmentation (Mastin, 2005; Hale and Mühlhaus, 2007; Lavallée et al., 2008; Tuffen et al., 2008). Textural evidence of shear localization has been described in felsic volcanics and is inferred from seismic and acoustic events (Stasiuk et al., 1996; Goto, 1999; Marti et al., 1999; Rust et al., 2004; Iverson et al., 2006).

Strain localization is typical in rocks and multicomponent fluids, foams, and suspensions (Lauridsen et al., 2004; Caricchi et al., 2007). Due to multiscalar strength heterogeneity in rocks, deformation is commonly localized into shear zones from microscopic to lithospheric scale (Regenauer-Lieb et al., 2008). In volcanic rocks, identification of localized strain and its implications is recent (e.g., Stasiuk et al., 1996).

Here we use common textural features in vesicle-rich aphyric and crystalline pumice, with foam-like texture, to argue that strain localization during viscous flow preceding explosive fragmentation is a general phenomenon in these fluids. Localization does not require unusually high initial strain rates, degrees of shear heating, or crystal-crystal interactions; instead, it results from the magnification of background variations in magma strength due to feedback processes. Localization explains shear bands in pumice that modify magma rheology and provide sites for runaway increases in strain rate that can lead to fragmentation.

RHEOLOGICAL BEHAVIOR OF VESICULAR MAGMA

The literature on magma rheology and strain localization focuses on the role of crystals in modifying the Newtonian magma rheology (e.g., Costa, 2005). Crystals may nucleate shear zones (Hale and Mühlhaus, 2007) and increase in crystallinity may localize shear zones (Soule and Cashman, 2005) controlling strain-rate–dependent shifts from Newtonian to non-Newtonian to Bingham behavior (Caricchi et al., 2007). While it is clear that strain localization controls much of the behavior of magma eruption through conduits and subsequent flow (Sparks et al., 2000; Tuffen et al., 2003), the role of bubbles in nucleating shear bands during magma flow and controlling magma rheology has received less attention.

In steady flow, the rheological effect of bubbles is twofold. At low capillary number ($Ca = \frac{r\dot{\varepsilon}\mu_s}{\Gamma}$, where r is bubble radius, $\dot{\varepsilon}$ is strain rate, μ_s is shear viscosity, and Γ is surface tension), bubbles act as rigid bodies, increasing the relative viscosity of the mixture; at high Ca, bubbles deform, providing free-slip surfaces for the fluid and decreasing relative viscosity (Rust and Manga, 2002; Stein and Spera, 2002; Llewellin et al., 2002). Therefore, a local increase in Ca beyond a critical value close to one can trigger a decrease in foam viscosity, localizing shearing.

In foams, surface tension effects lead to non-Newtonian behavior of otherwise Newtonian fluids. Experiments show that foam has a shear-thinning viscoelastic rheology with a yield strength (Khan et al., 1988; Kraynik, 1988). In dry foam Couette flow experiments, shearing is partitioned into viscously deforming high-strain-rate zones abruptly separated from elastically deforming unstrained zones where stress is below yield (e.g., Lauridsen et al., 2004). Yield strength in aqueous foam occurs above a critical vesicularity of 63%, and increases with vesicularity (Saint-Jalmes and Durian, 1999).

The combined effect of bubbles and crystals can be even more complex. Bagdassarov and Pinkerton (2004) showed that vesicular crystal suspensions are thixotropic (decreasing in viscosity with time), viscoelastic fluids with a yield strength, power law rheology, and a nonzero shear modulus. In high-strain-rate zones, localized deformation can lead to shear heating, viscosity decrease, and increased strain rate in a runaway process (Mastin, 2005).

Here we use rhyolitic pumice samples that are more likely to preserve magmatic deformation than less viscous magmas. We examine textures from multiple pumice clasts in the low-crystallinity, low-eruptive volume Monte Pilato pumice cone deposit at Lipari, Italy, and the high crystallinity, large volume pyroclastic flow deposit from Cerro Galan, Argentina. Sample vesicularities range from 60% to 65% (by He-pycnometry on pumice clasts; e.g., Klug and Cashman, 1996) and permeabilities range from 2×10^{-15} m^2 to 1×10^{-13} m^2 (Wright et al., 2006). Our study of numerous samples from these and other deposits indicates that these textures are common in silicic Plinian eruptions.

TEXTURAL EVIDENCE OF SHEAR LOCALIZATION

Aphyric samples of Monte Pilato pumice typically contain 50–1000-µm-wide bands of elongated vesicles separated sharply (over <20 µm or ~1 deformed vesicle width) from zones of subequant vesicles (Fig. 1A). In hand samples, vesicle elongation defines a tube pumice fabric (Wright et al., 2006). Tomographic images of pumice clasts reveal curviplanar domains of elongate vesicles oriented in multiple directions (Fig. 1A; Video DR1 in the GSA Data Repository[1]). These domains contain prolate vesicles that commonly merge,

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[1] GSA Data Repository item 2009258, Figures DR1–DR3, and Videos DR1 and DR2, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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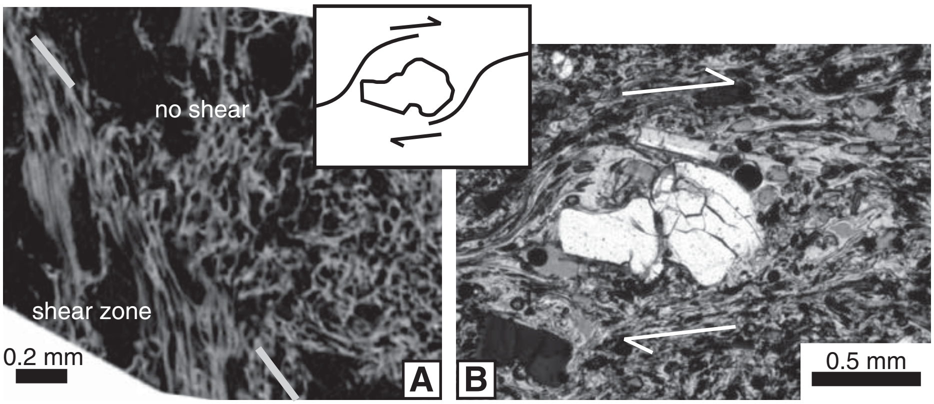

Figure 1. A: Synchrotron-based X-ray tomographic image of Monte Pilato pumice (from Advanced Light Source of Lawrence Berkeley National Lab). On left, 100–150 µm band of strongly elongated vesicles is >15 vesicles wide (vesicle widths approach 4.45 µm pixel size), in contrast with subequant vesicles on right (mode 24 µm diameter). B: Asymmetric vesicles around quartz crystal in Cerro Galan pumice define stair-stepping to right, as in dextral shearing in rocks (interpretation in inset). Plane polarized light photomicrograph.

forming nearly interconnected trails separated by thin glass walls (Video DR2).

Similar textures are found in highly crystalline Cerro Galan pumice clasts. In Figure 1B, a trail of stretched vesicles wraps around a quartz crystal with a stair-stepping asymmetry to the right, indicative of dextral simple shearing (e.g., Berthé et al., 1979). Pumice clasts are also characterized by localized bands of small and elongated vesicles nonadjacent to crystals, with sharp boundaries against domains of larger, subequant vesicles (Fig. 2A). Shape asymmetries of individual elongated vesicles (Fig. 2B) are paralleled by the asymmetry of their glass walls and the entire track of vesicles, and are analogous to experimental bubble shapes in simple shear (Li et al., 2000; Fig. DR1). The pointed ends of vesicles (Fig. 2B) indicate high *Ca* during deformation and lack of time for textural reequilibration.

In Figure 2C, a band of small, elongated vesicles is abruptly separated from an area of subequant vesicles. Close to the contact, vesicles show different degrees of elongation (Figs. 2D and 2E): a subequant vesicle (1 in Fig. 2E; aspect ratio = 0.58), an elongate asymmetric vesicle (2; aspect ratio = 0.17), and a curved trail of smaller, elongated vesicles (3; trail width/length = 0.02). This difference reflects increased shearing, with the trail of vesicles (3 in Fig. 2E) representing the most highly sheared and broken vesicle. Several small asymmetric vesicles in trail 3 indicate dextral shear sense (not visible in Figs. 2D and 2E). Figure 3 shows bands of elongated vesicles deflected around a region of subequant vesicles at a distance as great as two vesicle diameters away from crystals (due to the combined effect of surface tension between vesicles and crystals and strain shadows around crystals; Fig. 3). The left side of Figure 4A depicts a subtle example of localized strain. It contains a zone of small vesicles that define an asymmetric S-C-like fabric indicative of dextral shearing (Figs. 4B and 4C). Narrow glass bands with numerous <15-µm-wide and stretched vesicles also have asymmetries indicative of dextral shearing (Figs. 4D and 4E).

DISCUSSION

Strain Localization

The pumice clasts described above contain features interpreted to represent localized shear bands surrounded by unstrained or weakly strained zones where vesicles are larger and subequant. Shear bands are characterized by: (1) elongated vesicles and linear (curviplanar in 3-D) vesicle trails (estimated trail aspect ratios commonly >40:1, reaching 120:1); (2) small vesicle volumes compared to surrounding subequant vesicles, suggesting vesicle breakup resulting from stretching; (3) undulating glass walls defining a stair-stepping fabric akin to S-C fabric in solid rocks, in some places around

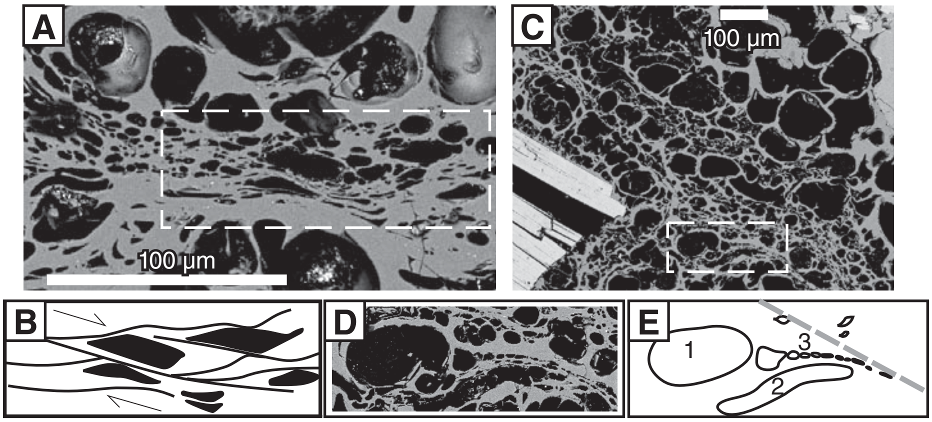

Figure 2. Backscattered electron images of deformed vesicles in Cerro Galan pumice. A: Band of elongated, asymmetric vesicles, >25 µm wide, is sharply separated from zones of rounded, subequant, and much larger vesicles. Large (>200 and 300 µm) biotite phenocrysts are present 120 and 150 µm above and below field of view, respectively. Vesicle asymmetry indicates dextral shearing. B: Interpretation of A. C: Narrow band of small vesicles (~5 µm wide, <500 µm long) trends diagonally from upper left to lower right between two crystals. D: Detail of C. Cluster of two vesicles and a vesicle trail near main shear band record different elongations. E: Line drawing of D; 1–3 indicate progressive increase in vesicle elongation. Asymmetric vesicles in upper right indicate dextral shearing. Gray dashed line marks center of shear band.

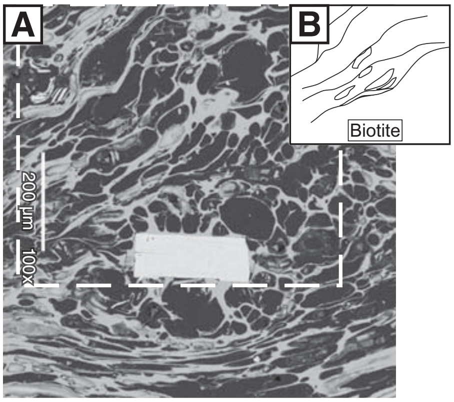

Figure 3. A: Backscattered electron image of two bands of elongated vesicles around subequant vesicles that surround central biotite crystal in Cerro Galan pumice clast. Horizontal band (below crystal) has symmetric vesicles (median aspect ratio of 0.26), indicative of pure shear. Diagonal band (above crystal) has asymmetric vesicles (median aspect ratios of 0.39) indicative of dextral shearing. White dashed line shows location of B. B: Schematic representation of asymmetric fabric in diagonal shear band above biotite crystal. Lines represent selected melt films between vesicles.

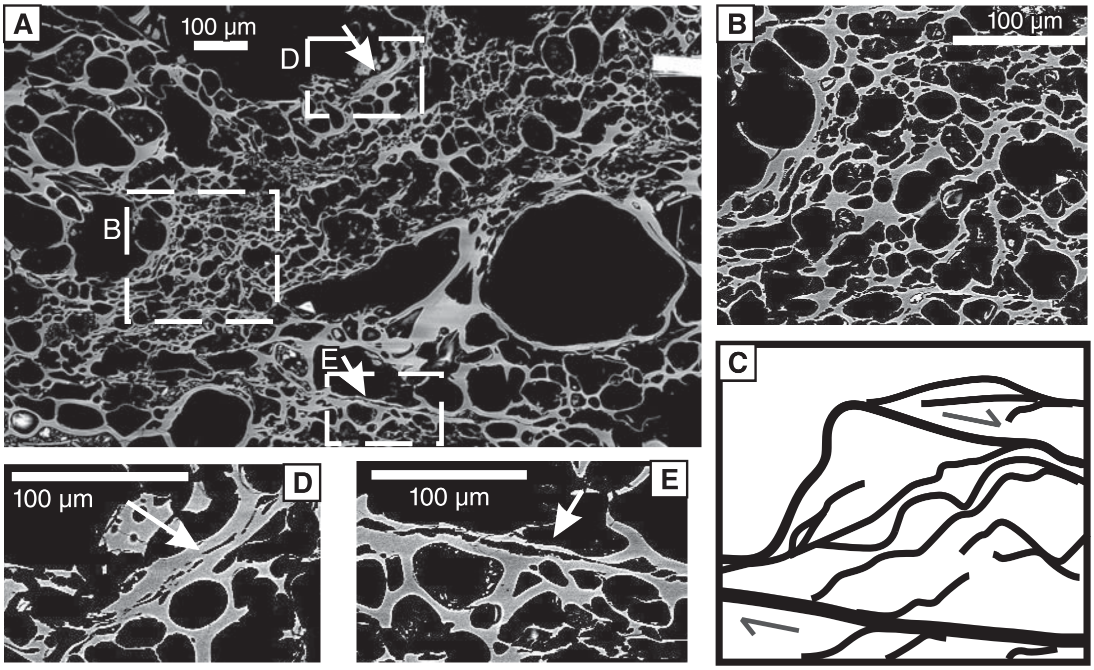

Figure 4. A: Domainal variations in heterogeneous pumice clast from Cerro Galan. Vesicle size varies by factor of 100, accompanied by fabric changes indicative of strain localization. B: Asymmetric vesicles and glass walls in region of small vesicles indicative of dextral shearing. C: Interpretation of fabric in B. Arrows indicate sense of motion. D: Trail of small, strongly elongated vesicles (arrow) <3 μm wide, with ~8-μm-thick glass walls. E: Small asymmetric vesicle trail, 2–15 μm wide, ~550 μm long (arrow), surrounded by much larger subequant vesicles. Vesicle wall thickness varies from 2 to 9 μm. Trails of small, sheared vesicles in (D–E) mark zones of localized shearing, stretching, and breakup of vesicles. Asymmetry in E indicates dextral shearing.

phenocrysts; (4) vesicle asymmetry indicating shear sense subparallel to vesicle wall stair-stepping; (5) typical shear band widths of 2 to >500 μm; and (6) sharp transition to domains lacking obvious shearing, indicative of steep gradients in strain rate (Figs. 2, 4D, and 4E). Combined, these features suggest localized simple or pure shear during magma flow, separated sharply from regions of negligible bulk strain. Shear zones are curviplanar features, continuous over several subequant vesicle radii lengths, and are not to be confused with individual bubble flattening by pure shear due to neighboring vesicle expansion (e.g., right edge of Fig. 4A).

Bubbles break up during deformation at constant strain rates and low Reynolds number when elongation exceeds 20 times the initial radius (gas/liquid viscosity ratios <1; Stone, 1994). In the pumice clasts shown, trails of vesicles have L/*a* ratios between 5 and 10 (where 2L is length of trail and *a* is the radius of a circle with the cumulative two-dimensional area of the trail; only linear trails with clear spatial relationships were measured; e.g., Fig. DR2). These values are lower than the critical value of 20 for breakup in homogeneous, constant-velocity flow. However, lower degrees of deformation may lead to breakup due to complexities of flow path, velocity, and vesicularity (cf. asymmetric bubble trails in experiments of Okumura et al., 2008). These vesicles have areas typically 1.5–250 times less than surrounding undeformed subequant vesicles (e.g., Fig. 4). The sum of the vesicle areas in a trail is less than one order of magnitude lower than neighboring subequant vesicles.

The asymmetric character of vesicles and asymmetric fabric defined by glass walls suggest a component of simple shear during deformation (Figs. 4B and 4E; Figs. DR1 and DR3). Glass wall asymmetry and vesicle asymmetry are analogous to S-C fabrics and sheared porphyroclasts in shear zones in solid rocks (cf. Berthé et al., 1979, their figure 5).

Sharp boundaries between vesicles with different degrees of stretching (e.g., Fig. 2D) could arguably result from variation in timing of bubble nucleation with respect to deformation. However, the relationship between proximity of vesicles to the shear band and degree of elongation (Figs. 2D and 2E) suggests that differences are related to variations in bulk strain across very short distances. We conclude that large variations in strain over length scales varying from a single thin glass wall to one or two vesicles wide mark zones of sharp change in strain rate during deformation. We argue that this is due to the existence of a yield strength in a foamy magma or strong feedback effects localizing deformation. Furthermore, most examined samples have varied shear band orientation and shear sense that do not define a sample-wide kinematic pattern. This suggests either heterogeneous flow or a complex flow history. Preservation of the shear bands is due to lack of time for textural reequilibration or to yield strength.

Feedback Effects

Strain localization results from the magnification of instabilities through feedback effects. Small variations in material properties (e.g., vesicularity, bubble, crystal, and/or temperature distribution, viscosity, or yield strength) nucleate shear bands by causing variations in strain rate that are amplified by feedback processes such as shear heating, elastic stress unloading of zones of lower strain rates, and changing role of vesicles with increasing *Ca* (Gruntfest et al., 1964; Llewellin et al., 2002).

Shear heating in aphyric, nonvesicular silicate glass becomes significant at strain rates above 10^{-3} s^{-1} (Hess et al., 2008). Distributed strain rates in conduits have been estimated to reach between 10^{-2} and 10^{-6} s^{-1} (Tuffen et al., 2003), though explosive eruptions may reach higher rates. Strain localization causes local strain rate increase in proportion to the degree of localization. Ratios between shear band width and interband spacing in our samples of 1:1.5–1:100 could lead to 1.5–100-fold increase in local strain rates, further enhancing the role of shear heating in triggering a runaway feedback effect.

The changing role of vesicles as a function of strain rate (*Ca*) is particularly important during initial stages of foamy magma flow. As the stress that initiates flow is increased, strain may localize to regions where *Ca* exceeds unity first. Once localized, further stress increase may not be distributed homogeneously, but may increase in weak zones, reinforcing strain localization by increasing local strain rates, defining a feedback loop. This is similar to the process of strain localization and shear band stabilization in solid rocks, where movement in the shear band allows heterogeneous stress distribution and unloading of elastic stresses accumulated elsewhere (Regenauer-Lieb et al., 2006).

We postulate that a combination of such processes leads to development of a pattern of anastamosing weak shear bands that may become a stable configuration of the deforming foam. Vesicle breakup, leading to an increase in *Ca* and possible strain hardening, could counteract this process and cause widening of shear bands (Mancktelow, 1988).

The development of shear bands and increase in strain rate may cause magma in the shear bands to cross the glass transition and lead to fragmentation. However, other mechanisms may also come into play during decompression and final fragmentation during eruption (e.g., overpressurization-induced bubble bursting). Strain localization implies that calculations using average strain rates across finite regions in typical piston or parabolic velocity profiles would underestimate local strain rate, and thus overestimate the strain rate necessary for explosive eruption.

IMPLICATIONS FOR CONDUIT FLOW

We have focused here on pumice shear zones at the scale of tens of microns, the scale required to document the nature and details of glass foam shearing. However, the scale of shear bands in these clasts can be larger (>500-µm-wide zones). We argue that given enough flow time, these bands could form a shear zone system anastamosing around regions of low bulk strain, and affect conduit flow.

The most complex models of conduit flow in volcanic systems consider shear thinning or heating against the conduit walls, resulting in a change from a typical Newtonian parabolic conduit flow to a piston-like flow (e.g., Hale and Mühlhaus, 2007). Our results suggest a complex flow and rheology of foamy magmas, as expected from the foam literature (Kraynik, 1988). Localization of deformation into bands driven by this rheology would amplify strain rates, providing localized sites for strain-rate–induced brittle fragmentation, and would affect conduit velocity profiles fundamentally and unpredictably.

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