Learning Science Through Research
Published by the Keck Geology Consortium
Short Contributions
Keck Geology Consortium
Volume 33
May 2020
doi: 10.18277/AKRSG.2020.33.15

# MICROLITE ORIENTATIONS AND STRAIN LOCALIZATION WITHIN THE BASAL SHEAR ZONE OF A LARGE RHYOLITIC LAVA, MINYON FALLS, AUSTRALIA

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## INTRODUCTION

The Minyon Falls Rhyolite is a large lava dome in the southern part of the Nimbin Rhyolite dome complex of the Tweed shield volcano in eastern Australia that was emplaced during the Early Miocene. In excess of 100 m thick and 4 km in diameter, the lava dome is comprised of a flow-banded obsidian overlain by banded crystalline rhyolite (Smith and Houston, 1994; Smith, 1996). Folds in the main mass of crystalline rhyolite record strains of <1 associated with gravity spreading during emplacement (Smith and Houston, 1994). In contrast, structures and textures of the basal obsidian indicate accommodation of large strains associated with shear roughly parallel to the base of the flow (Smith, 1996). To investigate the localization of strain within the basal shear zone, we consider the three-dimensional orientations of microlites within stratigraphically constrained samples of flow-banded obsidian from flow-front and near-vent localities. Because the degree to which microlites align during flow increases with increasing deformation, microlite orientation distributions can be used to infer flow properties such as flow type and strain (Manga, 1998; Castro et al., 2002).

## METHODS

### Theoretical Framework

When melt ascends through a shallow conduit, decompression and degassing result in the nucleation and growth of bubbles and microlites (Swanson et al., 1989; Toramaru, 2006). Variation in the concentration of microlites and/or bubbles often define a foliation common to silicic lavas referred to as flow banding (Manga, 2005). The textural characteristics and geometry of flow bands reflect the cumulative history of magmatic flow within the vent and at the surface. Here we take advantage of an integrated approach developed by Manga (1998) to gain quantitative insight into processes that occur during effusion of lava. Microlite orientations are measured in oriented thin-sections and are described by their trend (φ) and plunge (θ) as depicted in Figure 1. Comparison of measured distributions with those predicted by theory allows assessment of the type and magnitude of strain during flow.

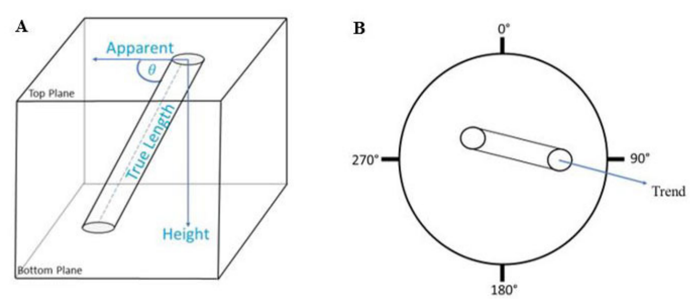


*Figure 1. Schematic diagram illustrating characterization of microlite orientation through trend (φ) and plunge (θ), adapted from Castro et al. (2002). A: 3D schematic of a microlite between two focal planes. The apparent length measured from the top plane, moving down to the bottom plane to gain the height allows for the plunge (θ) to be calculated. The true length is then derived from the Pythagorean Theorem. B: Goniometer is utilized to determine the trend of the microlite based on its long axis.*

The approach is underpinned by theoretical analysis of the motion of rigid rod-shape particles in dilute low-Reynolds-number shear flows (Manga, 1998). The equations for particle motion in simple shear flow are (Jeffery, 1992):

$$\frac{d\varphi}{dt} = \frac{G}{R^2+1}\left(R^2 \cos\varphi + sin^2(\varphi)\right) \quad \text{and}$$

$$\frac{d\theta}{dt} = G\,\frac{R^2-1}{R^2+1} sin\theta cos\theta sin\varphi cos\varphi,$$

while the equations for particle motion in pure shear flow are (Gray, 1966):

$$\frac{d\varphi}{dt} = G\,\frac{R^2-1}{R^2+1}\sin(2\varphi) \quad \text{and}$$

$$\frac{d\theta}{dt} = -\frac{1}{2}\frac{R^2-1}{R^2+1}\cos(2\varphi)\sin(2\theta)$$

where t is time (s), R is microlite aspect ratio, and G is strain rate ($s^{-1}$). The resulting three-dimensional orientation distributions can be conveniently characterized by the standard deviation (σ) of trend (φ) and plunge (θ). Using the equations given above, Manga (1998) showed that initially randomly oriented microlites in a simple shear flow progressively align in the direction of shear with increasing strain, but never perfectly align due to periodic rotation. In contrast microlites in a pure shear flow become perfectly aligned with increasing strain in the direction of extension. Therefore $\sigma_\varphi$ and $\sigma_\theta$ approach zero in pure shear, and finite constants in simple shear flows (Manga, 1998).

**Sample Background and Microlite Measurements**

The obsidian samples examined here were collected from within the basal shear zone of the Minyon Falls Rhyolite (Brown, 2010; Cook, 2011). The structural and textural features of the glassy base and overlying crystalline core of the rhyolite are documented by Smith (1996) and Smith and Houston (1995), respectively. The base of the flow is comprised of a breccia overlain by coherent, flow-banded obsidian. Within 500 m of the inferred vent, the glassy base of the lava is roughly 3 m thick, but is in excess of 20 m near the southern front of the flow, some 4 km from the vent. The intact, banded obsidian records intense ductile shearing in multiple folds, rotated phenocrysts, alignment of microlites, and micro-folding of microlite-defined flow bands. In the lower part of the basal obsidian, flow bands are often discontinuous and are cut by mesoscale and microscale faults at low angles. The underlying basal breccia is comprised of monolithic clasts that are variably plastically deformed, with strong alignment of elongated clasts at distal locations. The clasts also show internal ductile textures (e.g., flow banding, micro-folds, etc.) similar to that in the coherent obsidian above. Near the vent where the breccia is thin (~0.5m thick) and in the top meter of the breccia in distal sites, clasts are angular to sub-rounded with distinct margins. However, with increasing distance below the intact obsidian at distal locations, clasts become rounded and elongate, with less distinct boundaries. Clasts range in size from 15 cm down to microscopic fragments that are indistinguishable from the glassy matrix in the field.

Detailed analysis of the spatial relationships of the brittle and ductile structures outlined above led Smith (1996) to conclude that: (1) the breccia formed by shear-induced fragmentation at the base of the flow, rather than as an overridden surface breccia; and (2) the basal shear zone accommodated most of the deformation during emplacement, while the main mass of lava was translated above. To investigate how strain is distributed within the basal zone of shear, we examined microlite orientations from two locations within the glassy base of Minyon Falls Rhyolite. The first site, referred to as the near-vent site with sample numbers beginning with MR11, is located roughly 0.5 km northeast of the inferred vent and includes four stratigraphically controlled samples of the intact obsidian and one sample of a sub-rounded clast from the underlying breccia. The second site is located at the southernmost extent of the lava, about 4 km from the vent area. This site is referred to as the flow-front site and is represented by three samples beginning with MR02.2. These three samples are within the zone of the basal breccia showing brittle-ductile transition structures (Smith, 1996).

All thin-sections were cut perpendicular to layering defined by flow bands with the original sample orientation in mind, where the “up” direction is parallel with the greater length of the slide (Fig. 2). The stratigraphic order of the banded MR11 thin-sections are reflected as 9 at the top, 7, 6T, 6B (all within the intact obsidian), and sample 2 at the bottom, within the basal breccia; the MR02 thin sections are ordered from sample 2 at the top, 3 in the middle, and 4 at the stratigraphic bottom (Brown, 2010; Cook, 2011). The method employed to measure microlite


*Figure 2. Scan of thin-section MR11.7, showing microlite measurement sites (asterisks) for colorless and brown-colored flow bands along a vertical transect parallel to the stratigraphic "up" position of the oriented rock sample.*

orientations is depicted in Figure 1 and described in Seitzinger (this volume). The method is similar to the simplified approach of Befus et al. (2014), which was adapted from the digital reconstruction method of Manga (1998). Because of space limitations, the details of the method are not repeated here.

The micro-textural analysis conducted here takes advantage of the large microlite orientation dataset developed by Seitzinger (this volume), who concentrated on quantification and interpretation of microlite size and number densities with the rhyolite. To expand the stratigraphic coverage, additional analyses were undertaken as part of this project for sample MR11.9, which is representative of the upper half of the intact obsidian at the near-vent site. All other data was collected by Seitzinger (this volume). With each thin-section, data was collected for up to nine individual flow bands along a roughly vertical transect relative to the "up" direction of the slide (Fig. 2). Microlite orientation distributions were measured for 33 flow bands at the near-vent site and 15 flow bands at the flow-front site.

# RESULTS

## Microlite Orientations

The orientation distributions of microlites are characterized by the standard deviation (σ) of trend (φ) and plunge (θ), with uncertainties of about 1° and 5° respectively (Manga, 1998; Befus et al., 2014). Due to inherent better resolution, we focus our attention here on measured trend distributions. Results for stratigraphically controlled samples at the flow-front and near-vent locations are shown in Figure 3.

The largest number of microlite measurements are from the near-vent site, where the majority of flow bands display a high degree of a microlite alignment ($\sigma_\phi < 20°$). The exception is sample MR11.7, which is characterized by less-well aligned microlites with $\sigma_\phi$ values ranging from 24° up to 38°. Microlites are also well alignment at the flow front, although there is no apparent improvement in alignment despite flowing roughly 4 km from the vent. The mean values for $\sigma_\phi$ are statistically indistinguishable between both sites (Fig. 3).

Despite the overall high degree of a microlite alignment within the basal shear zone, orientation distributions vary by up to a factor of four among flow bands within individual thin-sections (e.g., MR11.6B). This small-scale heterogeneity does not correlate with flow-band type, as defined by glass color and microlite

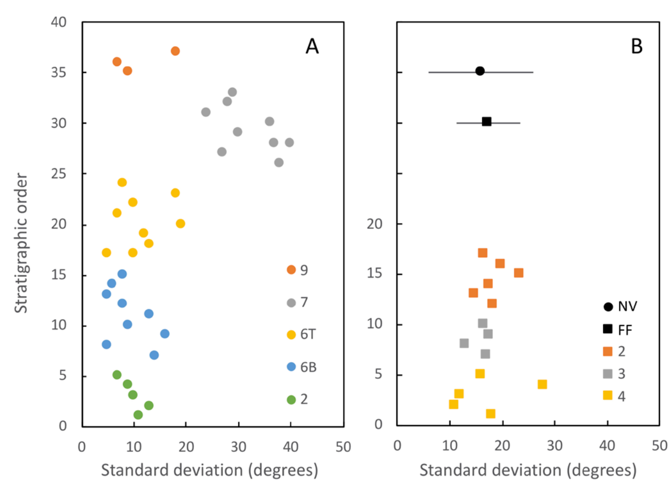


*Figure 3. Variation of standard deviation of microlite trend angles (x-axis) with relative stratigraphic height (y-axis) for near-vent, A, and flow-front, B, locations. Mean values for the near-vent and flow-front sites are labeled NV and FF, respectively, and are shown at the top of panel B.*

number density. Mean $\sigma_\phi$ values for all colorless and brown-colored flow bands analyzed are statistically indistinguishable (15±10° and 17±10°, respectively), and the goodness of fit, as expressed by $R^2$, for MND plotted against $\sigma_\phi$ (not shown) is less than 0.01 (MND data from Seitzinger, this volume).

**Strain Estimates**

The orientations of microlites and flow bands around rotated phenocrysts indicate that strain in the basal obsidian was primarily accumulated by simple shear (Fig. 4). Comparison of the measured microlite orientations to theoretically predicted distributions of slender rods in a Newtonian fluid in simple shear flow (Manga, 1998) yields strains ranging from 2 up to about 10 for most flow bands in both near-vent and flow-front positions. However, about a third of the flow bands yield standard deviations for trend angles that indicate infinite strain, assuming flow by simple shear alone. These low $\sigma_\phi$ values (down to 5°) appear to require a component of pure shear (e.g., Befus et al., 2014). Assuming pure shear alone, our $\sigma_\phi$ values indicate shear strains of up to about 3 (Manga, 1998). It seems likely that most of the microlite distributions reflect re-alignment in some combination of pure and simple shear flow. In any event, these strain estimates are high compared to those obtained for surface samples elsewhere (Castro et al., 2002; Befus et al., 2014; 2015).


*Figure 4. Photomicrographs showing deformation of flow bands around micro-phenocrysts, consistent with simple shear (from sample MR11.9).*

# DISCUSSION & CONCLUSIONS

Preliminary analysis reveals little to no systematic variation of microlite trend alignment with stratigraphic or lateral position within the basal shear zone of the Minyon Falls Rhyolite. With few exceptions, microlites are well aligned within the intact flow-banded obsidian and the underlying basal breccia. The degree of alignment is noticeably high compared to microlite orientation distributions measured for samples representative of the upper surfaces of rhyolite lava flows and domes (Befus et al., 2014; 2015). The high degree of microlite alignment at the base of the flow is consistent with numerical results indicating that most of the strain associated with emplacement of viscous rhyolite lava is accommodated within a basal zone of shear, while the main mass of lava is rafted above (Befus et al., 2015).

Although the shapes of flow bands deformed by phenocrysts are consistent with simple shear (Fig. 4), some flow bands display microlites of too well alignment to have experienced simple shear alone. The apparent combination of pure and simple shear hinders an attempt to uniquely constrain the strain responsible for microlite alignment. Nevertheless, our measured orientation distributions for both flow-front and near-vent sites yield similar mean strain estimates (approaching 2 and 6 for pure and simple shear, respectively) for each site, based on mean values for the standard deviation of trend angles (Fig. 3).

A lack of improvement of microlite orientation with distance from the vent (Fig. 3) has been observed for surface samples from both small and large rhyolite lavas (Befus et al., 2014; 2015). One explanation for this lack of increased alignment with distance traveled on the surface is that microlite alignment is inherited from flow in the conduit and that flow at the surface was unable to further align microlites (Befus et al., 2014; 2015). This scenario seems likely for the upper portions of flows, where folds indicate strains less than 1 (Smith and Houston, 1994), but it is unlikely to apply to the base of rhyolite lava flows and domes where most of the strain associated with emplacement is expected to be concentrated. Although basal shear appears to be capable of improving the alignment of microlites from that potentially imparted in the conduit, it does not systematically increase microlite alignment with distance travel during subaerial flow. This observation is consistent with a model whereby the zone of basal shear migrates upward into the overlying lava as the flow advances (Smith, 1996).

## ACKNOWLEDGEMENTS

This material is based upon work supported by the Keck Geology Consortium and the National Science Foundation under Grant No. 1659322.

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