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Thermomechanical milling of accessory lithics in volcanic conduits

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ABSTRACT

Accessory lithic clasts recovered from pyroclastic deposits commonly result from the failure of conduit wall rocks, and represent an underutilized resource for constraining conduit processes during explosive volcanic eruptions. The morphological features of lithic clasts provide distinctive 'textural fingerprints' of processes that have reshaped them during transport in the conduit. Here, we present the first study focused on accessory lithic clast morphology and show how the shapes and surfaces of these accessory pyroclasts can inform on conduit processes. We use two main types of accessory lithic clasts from pyroclastic fallout deposits of the 2360 B.P. subplinian eruption of Mount Meager, British Columbia, as a case study: (i) rough and subangular dacite clasts, and (ii) variably rounded and smoothed monzogranite clasts. The quantitative morphological data collected on these lithics include: mass, volume, density, 2-D image analysis of convexity (C), and 3-D laser scans for sphericity (Ψ) and smoothness (S). Shaping and comminution (i.e. milling) of clasts within the conduit are ascribed to three processes: (1) disruptive fragmentation due to high-energy impacts between clasts or between clasts and conduit walls, (2) ash-blasting of clasts suspended within the volcanic flux, and (3) thermal effects. We use a simplified conduit eruption model to predict ash-blasting velocities and lithic residence times as a function of clast size and source depth, thereby constraining the lithic milling processes. The extent of shape and surface modification (i.e. rounding and honing) is directly proportional to clast residence times within the conduit prior to evacuation. We postulate that the shallow-seated dacite clasts remain subangular and rough due to short (<2 min) residence times, whereas monzogranite clasts are much more rounded and smoothed due to deeper source depths and consequently longer residence times (up to ~1 h). Larger monzogranite clasts are smoother than smaller clasts due to longer residence times and to greater differential velocities within the ash-laden jet. Lastly, our model residence times and mass loss estimates for rounded clasts are used to estimate minimum attrition rates due to volcanic ash-blasting within the conduit (e.g., 12 $cm^3\,s^{-1}$ for 25 cm clasts, sourced at 2500 m depth).

1. Introduction

Accessory lithic clasts recovered from pyroclastic fallout deposits are an underutilized resource for understanding the processes operating in volcanic conduits during explosive eruptions. Lithic clasts result from syn-eruptive fragmentation of conduit wall rocks and are entrained into the rapidly ascending stream of erupting material. Here, we use the size, morphology and textural properties of accessory lithic clasts to elucidate the "*milling*" processes operating in volcanic conduits during explosive eruptions.

The pyroclastic fallout deposit of the 2360 B.P. eruption of the Mount Meager Volcanic Complex in British Columbia, Canada (Fig. 1), contains two main types of accessory lithic clasts: (i) rough and subangular dacite clasts, and (ii) smooth and rounded monzogranite clasts. Milled or highly rounded accessory lithics have been reported in many other pyroclastic deposits; examples include Santorini (Mellors and Sparks, 1991), the Meidob volcanic field in Sudan (Franz et al., 1997), the Kaingaroa ignimbrites of New Zealand (Nairn et al., 1994), and the Kos Plateau Tuff, Greece (Allen and Cas, 1998). Nairn et al. (1994) observed that the largest lithics in the Kaingaroa ignimbrites were typically the roundest, and suggested that they were shaped through repeated fall back and milling in the vent(s). Mellors and Sparks (1991) noted that many of the rounded lithics at Santorini display concentric rinds of altered rock, and attributed the rounding of these lithics to the abrasion of these fragile rinds during eruption and transport. To date, however, there have been no detailed studies of the processes or timescales associated with the volcanic milling of lithic clasts.

Here, we have used a variety of techniques, including 2-D image analysis and 3-D laser scanning, to describe and quantify the morphological properties of accessory lithic clasts recovered from the Mount Meager 2360 B.P. fallout deposits. Our analysis of these datasets suggests three main processes control clast size, shape

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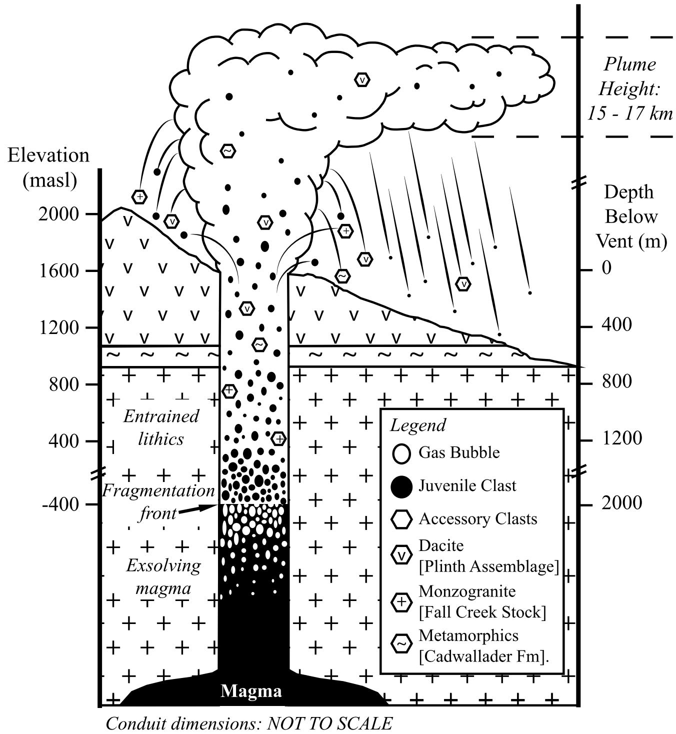

Fig. 1. Schematic cross-section through the conduit of the 2360 B.P. eruption of Mount Meager illustrating the country rock stratigraphy and source locations for the accessory lithic clasts found in fallout deposits. The fragmentation surface is likely to have varied in time but propagated to depths well in excess of 700–800 m below the vent (see text). Vertical conduit dimensions are to scale; horizontal scale is schematic.

and surface properties: (1) disruptive fragmentation (e.g., Dufek et al., 2012), (2) "*ash-blasting*" (i.e. sandblasting by volcanic ash), and (3) thermal effects. We conclude our study with a model for the comminution and reshaping of accessory lithic pyroclasts during explosive volcanic eruptions that constrains the mean diameter of the volcanic conduit, relates the shape and smoothness of individual clasts to residence time within the volcanic conduit, and establishes the amounts and rates of clast attrition.

2. Field site: the Mount Meager Volcanic Complex

The Mount Meager Volcanic Complex (MMVC) is a calc-alkaline volcanic complex located in southwestern British Columbia, Canada, at the northernmost extent of the Cascade Volcanic Arc (Green et al., 1988; Read, 1990; Sherrod and Smith, 1990). The MMVC consists of a number of partially overlapping volcanoes which produced pyroclastic deposits, lava flows and domes, and rock avalanche deposits from >1.9 Ma to recent times (Read, 1977a, 1977b). The youngest eruption of the MMVC is dated at 2360 B.P. (Clague et al., 1995) and produced the Pebble Creek Formation (PCF). The PCF deposits are predominantly dacitic in composition, and their geology is described in detail elsewhere (Hickson et al., 1999; Michol et al., 2008; Read, 1977a, 1977b, 1990; Stasiuk et al., 1996; Stewart et al., 2002, 2008).

The subplinian phase of the 2360 B.P. eruption (VEI = 4) generated a plume 15–17 km in height, and formed pumiceous pyroclastic fallout deposits totaling $\sim 4.2 \times 10^8$ m^3 in volume (Andrews et al., in preparation; Hickson et al., 1999). The fallout deposits mantle the slopes of the mountainous terrain towards the northeast of the MMVC. Vent-proximal deposits of this tephra reach thicknesses of ~80 m (Hickson et al., 1999); very fine-grained, thin distal layers of the ash are identified in Alberta ~500 km distance from the vent (Nasmith et al., 1967; Westgate and Dreimanis, 1967).

The fallout deposits are unconsolidated, well-sorted and clast-supported, and comprise mainly juvenile, white to cream-colored pumice clasts. There are four main types of accessory lithic clasts within the fallout deposits (Campbell, 2012; Stasiuk et al., 1996; Stewart, 2002). This research focuses on the properties of the two most abundant types: grey, porphyritic dacite (Plinth Assemblage), and pale-pink, medium- to coarse-grained monzogranite (Fall Creek Stock) (Fig. 1). The accessory lithic clasts originate from country rock underlying the vent and source depths are estimated from surficial geology and drill hole data (Campbell, 2012).

3. Methodology

3.1. Sample collection

Monzogranite and dacite accessory lithic clasts from the PCF fallout deposits were recovered from two localities. A total of 109 monzogranite and 39 dacite lithics, ranging in size from 6 to ~20,000 cm^3 and from 29 to ~12,000 cm^3, respectively (Supplementary Appendix A), were sourced from proximal fallout deposits situated in the Great Pacific Pumice quarry ~2 km north of the 2360 B.P. vent (50°40′54″ N, 123°30′43″ W). Another 51 monzogranite and 42 dacite lithics, ranging in size from 0.1 to 20 cm^3 and from 0.2 to 123 cm^3, respectively (Supplementary Appendix A), were collected from an outcropping of fallout deposit ~4 km east-northeast of the vent (50°40′15″ N, 123°27′16″ W). The relative abundances of lithics in the latter deposit is ~4 wt.% dacite, ~2 wt.% monzogranite, and <2 wt.% for other lithics (Campbell, 2012). These abundances probably overestimate the total volume of accessory lithics contained within the fallout deposit because of the vent proximal nature of these outcrops (e.g., Varekamp, 1993).

Clast volume (V) was calculated from measured values of mass and density using the Archimedes wet–dry technique (e.g., Hutchison, 1974). The mean densities of the monzogranite and dacite sample sets are 2.59 ± 0.01 g/cm^3 and 2.47 ± 0.10 g/cm^3, respectively (Supplementary Appendix A). Representative samples, spanning a range of sizes, for the two clast types are shown in Fig. 2.

3.2. Qualitative morphological analysis

The dacite lithics are subangular, equant to slightly elongate in form, and feature rough surfaces commonly bounded by prominent, or sharp, edges (Fig. 2b). A substantial number of dacite clasts feature one or more relatively smooth, planar, sometimes oxidized, surfaces that clearly originated as cooling joint surfaces (i.e. columnar jointing; Fig. 3c). Conversely, the monzogranite clasts are generally rounded to subrounded, and equant to elongate in form (Fig. 2a); larger clasts are commonly ellipsoidal in shape and their overall roundness and smoothness increases with increasing clast size. Some honed monzogranite clast surfaces feature concentric, partially detached, mm-scale flakes. Monzogranite clasts sometimes host two distinct surface types where the smooth, rounded exterior surfaces are truncated by relatively rough and planar surfaces bounded by sharp edges (e.g., Fig. 3a). These latter faces represent relatively late (i.e. post smoothing) breakages of the milled monzogranite clasts, suggesting that many monzogranite clasts undergo disruptive collisions immediately prior to their ejection from the conduit. In several samples, the late fracture surfaces truncate the highly smoothed surface of a rounded monzogranite clast but have, themselves, been subsequently milled to varying degrees (e.g., Fig. 3b). On the basis of these observations, the monzogranite sample set was subdivided into two categories: (1) "intact" monzogranites, having ⩾90% rounded and smoothed surfaces (e.g., Fig. 2a); and (2) "broken" monzogranites, with <90% rounded and smoothed surfaces (e.g., Fig. 3a).