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Evolution of the mechanics of the 2004–2008 Mt. St. Helens lava dome with time and temperature

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ABSTRACT

The 2004–2008 eruption of Mount St. Helens, Washington, USA, formed a typical example of a Pelean spiny lava dome, with solid spines of crystalline silicic lava extruded along shear zones bounded by fault gouge (Cashman et al., 2008; Iverson et al., 2006). Creation of and movement along shear zones in this erupting lava, recorded as shallow micro-earthquakes, were thus key controls on eruption style and rate, in addition to dome stability. As eruption style and lava dome stability often change within individual eruptions, it is important to identify how the strength of dome rocks changes with temperature, time, texture and extrusion rate. However, critical values of the shear strength of dome lava at eruptive temperatures have never been measured. We have found in controlled laboratory experiments simulating eruption conditions that dome lava strength increased during the course of the 2004–2008 eruption of Mount St. Helens, as the textures became more crystalline and less porous. Increasing lava strength during the eruption would lead to deformation becoming increasingly localised to shear zones, explaining why the extrusion style and centre were so consistent. Acoustic emissions and microstructure analysis indicate that fracturing was more localised at higher temperatures, resulting in higher strengths at eruptive temperature compared to ambient temperatures for later erupted samples. The strength of these later erupted samples at eruptive temperatures increased markedly with strain rate. This would damp any increases in effusion rate that may result from changes in magma pressure, explaining the steady effusion rate at Mount St. Helens from 2004 to 2008.

1. Introduction

Lava domes can have a wide range of morphologies, from a collection of steep sided spines, to a few blocky lobes, to a single blocky mound (Fink and Anderson, 2000). Their eruption style, morphology, and stability often change within individual eruptive episodes (Nakada et al., 1999; Watts et al., 2002), with hazardous dome collapse and explosive activity often associated with these changes. Given that extrusion is often facilitated by shear failure planes and that dome collapse typically results from a loss of material cohesion, it is important to understand how the strength of dome rocks can change with temperature, time, texture, and extrusion rate. Lava dome extrusion and changes in eruptive behaviour are typically preceded and accompanied by numerous shallow small earthquakes (Neuberg, 2000; Smith et al., 2007), so further insights into how these indicators vary under different conditions are also needed. We address these issues by deforming lava dome rocks in the laboratory, under temperature, pressure and deformation rate conditions of active lava domes and shallow magma conduits. From this, we are able to determine how the strength and deformation style vary with the lava properties and conditions they are subjected to. Recording acoustic emissions (AE) during these experiments, enables us to relate the different deformation conditions and mechanisms to the amount of seismicity they would generate.

The 2004–2008 Mount St. Helens (MSH) lava dome, an example of a spiny lava dome, was chosen for this study due to the availability of samples collected directly from the well monitored growing lava dome at different stages of the eruption, with accurate time constraints on when the samples were erupted (Thornber et al., 2008). This episode of activity at MSH began in late September 2004, when, after 18 yrs of quiescence, intense shallow seismicity (mostly less than 1 km; Iverson et al., 2006; Thelen et al., 2008), localised surface uplift, and steam and ash venting (Scott et al., 2008) were observed. After some small initial explosions, a solid spine of crystalline dacite, bounded by fault gouge, emerged on 11 October 2004 (Cashman et al., 2008; Scott et al., 2008). The dome complex grew continuously until January 2008, through a combination of lava spine extrusion and endogenous growth (Major et al., 2009). Two minor spines appeared in October 2004, followed by two larger spines, which grew and crumbled between late October 2004 and April 2005 (Major et al., 2008; Vallance et al., 2008). Spine 5 then emerged, grew and crumbled between April and August 2005, followed by spine 6, which was quickly enveloped by the emergence of another

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spine complex in October 2005 (Major et al., 2008; Vallance et al., 2008). This was a major spine that engulfed several smaller spines and combined with endogenous growth to form a broad mass known collectively as spine 7 (Major et al., 2008; Vallance et al., 2008), which grew continuously until January 2008 (Major et al., 2009). Though much of the volumetric growth of spine 7 was endogenous, this growth had a localised focus and slabs of fresh lava could frequently be seen at the peak of the spine complex, in a remarkably consistent position (Major et al., 2009). Given that partitioning of dome growth into endogenous and exogenous extrusion is a natural consequence of dome growth (Hale and Wadge, 2008; Watts et al., 2002), the localised focus indicated a relatively stable stress distribution and a persistent path of least resistance for eruption from the conduit (Major et al., 2009). That is, the growth patterns at MSH indicate that the dome morphology was influenced predominantly by external topographic and internal structural controls, rather than conduit processes (Major et al., 2009; Vallance et al., 2008).

Though many lava domes grow in a series of shorter bursts, including the earlier 1980–1986 activity at MSH (Swanson and Holcomb, 1990), the growth in 2004 to 2008 was continuous for over 3 yrs. The extrusion rate decreased monotonically from >6 m^3/s in October 2004 to zero in early 2008 (Major et al., 2009; Schilling et al., 2008) and the linear extrusion rate decreased from 15 m/d to 1 m/d during the periods of exogenous growth where this rate could be determined (Vallance et al., 2008), reaching a total extruded volume of ~120 million m^3. The exposed spines were all bounded by a 1–3 m thick gouge zone (Cashman et al., 2008). Regular small, shallow hybrid earthquakes, dubbed 'drumbeats', interspersed with small sporadic volcano-tectonic earthquakes, continued throughout the eruption (Moran et al., 2008). This is in contrast to the 1980 to 1986 activity at MSH, when earthquakes always subsided once extrusions began (Smith et al., 2007). The small VT events are believed to arise from brittle fracture in the edifice, whilst the characteristics of the 'drumbeat' events were a hybrid between VT characteristics and low frequency earthquake characteristics, where the low frequency component is believed to be caused by fluid movement (Moran et al., 2008). Iverson et al. (2006) proposed a model for the MSH lava dome extrusion and earthquake generation, where a plug of solid dacite extruded along gouge filled shear zones, with repetitive stick-slip movements at the margins of this plug generating repeating 'drumbeat' earthquakes and representing mechanical oscillations about an equilibrium. Key aspects of this model were that the frictional damping must be rate dependant and that the stiffness of the fault gouge must be greater than that of the magma beneath the ascending solid plug, in order for the ascent rate to oscillate without growing unstably or decaying.

Previous laboratory studies investigating the mechanical behaviour of the 2004–2008 erupted material were room temperature experiments focussing on the formation and properties of the fault gouge that accompanied the 2004–2008 eruption (Iverson et al., 2006; Kennedy et al., 2009; Moore et al., 2008). It was argued that these room temperature experiments were a valid representation because the extruding dacite was a crystalline solid with thermal image basal temperatures of ~700 °C (Vallance et al., 2008), far below the solidus of 950 °C, and because gouge formed in these room temperature experiments had a similar size distribution to natural gouge formed during spine extrusion (Kennedy et al., 2009). Indeed, the conventional rock physics view, based on studies of diverse rock types, is that there is little temperature effect within the brittle deformation field, save for a slight weakening (Paterson and Wong, 2005). This was the case in recent studies of triaxial deformation of andesite and basalt at temperatures up to 900 °C and strain rates comparable to typical lava spine extrusion rates (Rocchi et al., 2004; Smith et al., 2009).

The friction experiments on MSH fault gouge by Moore et al. (2008), showed that the gouge would exhibit rate and state dependant behaviour, and that it was stiffer than the magma source, which were key findings to validate the model of Iverson et al. (2006). Alternatively, Kennedy et al. (2009) argued that the 'drumbeats' would be caused by small increments in the shear fracture surface along which the dacite ascended (rather than slip along the gouge lubricated fault); based on fault gouge and fractures formed in their room temperature triaxial compression experiments on intact lava dome samples. This argument is compatible with the Neuberg et al. (2006) model for triggering similar repeating earthquakes at Montserrat, where they propose that fracturing of lava as it crosses into the brittle deformation field in a consistent position triggers repeatable low frequency volcanic earthquakes, due to the proximity of this repeated fracture position to the ductile magma.

Acoustic emission (AE) monitoring is often used in laboratory rock physics studies to detect, locate, and determine the size and focal mechanism of cracking events in the rock sample. They have been shown to correlate with the location and amount of cracking (Lockner et al., 1992; Sammonds et al., 1992; Thompson et al., 2006), and to have a similar fractal scaling (Main et al., 1990) and waveform characteristics including frequency size scaling (Benson et al., 2010) to tectonic-type earthquakes. Previous AE studies applied to volcanology have compared the characteristics of volcanic earthquakes with AE emitted during rock cracking, fluid flow, and a combination of these mechanisms (Benson et al., 2008, 2010; Burlini et al., 2007). Further studies have demonstrated that AEs occur from brittle fracture during deformation of silicic lavas at eruptive temperatures, from 600 to 1000 °C (Lavallée et al., 2008; Smith et al., 2009; Tuffen et al., 2008). However, whether the amount and timing of AE vary with temperature and sample texture has not been investigated.

Here we deform MSH 2004–2008 dome lava, whilst monitoring AE, in uniaxial and triaxial compression. We compare lavas extruded at different times (with different textures), deforming them at ambient and eruptive temperatures (750 to 970 °C), and different deformation rates. We are thus able to assess how the mechanical behaviour of the dome material and the amount and timing of AE varies with the extrusion date, deformation temperature, and deformation rate of samples. We relate this to how the magma properties influenced the extrusion style and earthquake generation.

2. High temperature deformation of dome lava

2.1. Sample descriptions

During the 2004–2008 eruption of MSH, the Cascades Volcano Observatory collected samples directly from the growing spines, using a steel box dredge suspended beneath a helicopter (Pallister et al., 2008). Using extrusion rates calculated from digital aero-photogrammetry (Schilling et al., 2008; Vallance et al., 2008) and the time and height from which the samples were collected, their extrusion dates were calculated (Thornber et al., 2008). The good time constraints on these samples, combined with the high quality seismic and geodetic monitoring of the eruption, make this the ideal suite of rocks for investigating the high temperature mechanics of dome lava experimentally. Specimen blocks used in this study were catalogued in Thornber et al. (2008) and are numbered according to that catalogue in this paper. Intact samples with no deformation textures from different phases of the eruption were chosen, so that we could assess how samples from different phases of the eruption would deform under different conditions. Samples from the first 2 yrs of the eruption had uniform bulk chemistry, with ~65 wt.% SiO_2 (Pallister et al., 2008). The phenocryst volume fraction was also uniform, but the glass fraction decreased from >30% to <2% (Pallister et al., 2008) and the porosity dropped to less than half of its original value during the eruption. Eruption dates of specimen blocks analysed in this study and the extrusion rates on these dates are shown in Table 1, together with a summary of their physical properties. Note that the initially-high porosity and glass content drop to minimum values of 8.0% and <2% for sample SH315-4, extruded in March 2005, then remain similar for