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Extreme frictional processes in the volcanic conduit of Mount St. Helens (USA) during the 2004–2008 eruption

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ABSTRACT

The 2004–2008 eruption of Mount St. Helens saw the extrusion of seven high-viscosity spines and formation of discrete shear zones along the conduit margin. At spine 7 this shear zone consists of four structurally distinct layers: the outer surface gouge (L1) crosscuts; a dark, banded layer (L2) which grades into; a moderately sheared layer (L3) and; undeformed rock (L4) inside the spine. Field observations, porosity measurements, geochemistry, mineralogy, microstructure, crystal size- and shape-distribution, kinetic properties and magnetic analyses chart the evolution of deformation processes and products throughout the eruption.

Gouge formation was concomitant with characteristic microseismic "drumbeats" at depths 0.5–1 km. In addition, the seismic record shows two larger earthquakes with similar seismic signatures in August 2006, which we conclude represent larger slip amounts along the conduit margin of spine 7. Extensive slip resulted in frictional heating on the order of several hundreds of degrees, melting the highly-viscous, crystalline, ascending magma plug and forming a pseudotachylyte. High ambient temperatures in the conduit resulted in near-equilibrium melting and slow recrystallisation, thus impeding the development of signature pseudotachylyte characteristics and hindering identification. Thus, frictional melting and recrystallisation in ascending magma plugs may be a common, but unidentified, phenomena at composite volcanoes worldwide.

1. Introduction

1.1. Frictional processes

During volcanic eruptions, the extrusion of high-temperature, high-viscosity magmatic plugs imposes frictional contact against conduit margins in a manner analogous to seismogenic faults. The near-solidus-temperature of extruding spines at Mount St Helens (USA) during the 2004–2008 eruption means extrusion was controlled by structural rather than magmatic processes (Vallance et al., 2008). The dynamics of seismogenic faulting is currently a highly active area of research in theoretical (Smith and Kilburn, 2010; Smith et al., 2007), experimental (Benson et al., 2008, 2010; Lavallée et al., 2008; Smith et al., 2009) and structural (Tuffen and Dingwell, 2005; Tuffen et al., 2003) volcanology.

Variation of differential stress, such that the Coulomb criterion for shear failure is exceeded, initiates ruptures in rocks on a laboratory to tectonic scale. Fault products depend upon slip rates and the friction coefficient of the ruptured material (Paterson and Wong, 2005; Scholz, 2002) and are governed by the tectonic setting and P-T conditions following the classification of Sibson (1977).

Within volcanic systems, background temperatures are significantly higher than the geotherm permits in other upper-crustal locations, whereas confining pressures are much lower than in high-temperature, lower-crustal settings: thus via their exceptional ambient P-T conditions, volcanic systems represent unique environments for faulting. Here, we assess the deformation mechanisms that took place during the extrusion of spine 7 at Mount St. Helens and discuss the potential for frictional melting along volcanic conduit margins.

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1.2. Mount St. Helens background

Mount St. Helens (MSH) is the most active member of the Cascade Volcanic Arc, which stretches along the West coast of North America from British Columbia (Canada) through to Northern California (USA). September 2004 marked the onset of the most recent eruption, indicated by localised ground uplift and shallow seismicity, followed swiftly by small gas-driven explosions (Scott et al., 2008). Subsequent extrusion of a lava dome as a solid plug began on October 11th. The growth continued until January 2008, forming a series of seven spines (Thornber et al., 2008). The spine margins were covered by a ~1–3 m thick, continuous layer of gouge with multiple planes of slickensides (Cashman et al., 2008; Kennedy et al., 2009) and was interpreted as an important control on ascent and extrusion.

The spines initially extruded at rates of 5.9 $m^3 s^{-1}$, and slowed to 0.7 $m^3 s^{-1}$ later in the eruption (Schilling et al., 2008). The early spines extended directly south, with spines 3–5 (October 2004–July 2005) showing a whale-back morphology (Scott et al., 2008). The vent remained in an almost constant position during the early extrusion of the spines (Scott et al., 2008), but during later stages (Autumn 2005 onwards), spine 7 took on a dome-like morphology which spread to the West of the previous spines (Vallance et al., 2008). [For the temporal evolution of the dome growth see Vallance et al. (2008) and Herriott et al. (2008).]

Extrusion of the spines was accompanied by repetitive or "drumbeat" seismicity (Iverson et al., 2006; Matoza and Chouet, 2010). "Drumbeats" were long period (LP) or hybrid, M 0.5–1.5 events, generally located at <1 km depth (Thelen et al., 2008) and occurred at intervals of 40–80 s, based on daily averaged values (Moran et al., 2008). The seismic signature of dome extrusion at MSH has been described as fundamental to the distinction of source mechanisms and thus the underlying mechanical processes. Two sources of the "drumbeat" seismicity have been postulated, and there is evidence for each. Iverson et al. (2006) first proposed that stick-slip motion, an inevitable consequence of rate-weakening frictional slip (Moore et al., 2008) occurred along the surface of the spines, citing evidence in the form of fault gouge, slickensides and cataclasite. This linked the micro-seismicity to ~5 mm slip events along the conduit margin. Waite et al. (2008) analysed the waveform of the LP events and identified dilatational first motions, which indicate a net volume decrease of the source. Thus it was concluded that the "drumbeats" were more likely formed by resonance in a gas-filled horizontally aligned crack or chamber at ~1 km depth in the conduit (Matoza and Chouet, 2010). These apparently conflicting models represent end-member possibilities, whereas the cause of the "drumbeats" was likely a combination of such factors created by the complexity of the volcanic system. Indeed Neuberg et al. (2006) indicated that resonance in a crack or chamber may in fact be initiated by stick-slip events. Irrespective of the cause of the "drumbeats", their production was contemporaneous with the formation of gouge and other fault-like features noted along the spine margins (Kennedy and Russell, 2012; Kennedy et al., 2009).

Larger, impulsive or emergent seismic events (M 2.0–3.6) also occurred sporadically throughout the 2004–2008 eruption, and were generally LP or hybrid, many having negative first arrivals, similar to, but larger than, the "drumbeats". Both frequency and source depth of these events were also akin to the "drumbeats", though radial locations have a smaller spread of only 1 km^2, which could be a result of the increased accuracy derived from larger signals. These similarities indicate that if the source mechanism of the "drumbeats" is stick-slip, then these larger events could represent a larger slip amount on the same slip surface (Iverson et al., 2006), thus magnitude varies as a function of slip and seismicity is produced by lurching of the spine like the upward thrusting of a piston (Moran et al., 2008). Few volcano-tectonic (VT) earthquakes occurred during the eruption, with the exception of the very earliest onset of seismicity in September 2004 and a nine day interval at the end of December 2005 and start of January 2006 when 70 earthquakes occurred at <0.3 km. When events were recorded, they were generally of low magnitude ($M < 1.0$) and shallow depth (<2 km). Moran et al. (2008) infer that the VT events correspond to brittle processes in the underlying rocks of the crater floor perhaps in a manner similar to hydraulic fracturing of the conduit wall (Chadwick et al., 1983). The failure induced in the conduit wall material would result in a static stress-drop, temporarily promoting movement along the conduit margin, thus altering the shallow frictional conditions of the extruding spines.

The holocrystalline, low-porosity nature of the dacite involved has led to the inference that crystallisation occurred as a result of devolatilisation at depths of approximately 1 km (Cashman et al., 2008). Petrographic analysis of the dome lava reveals a microlite-rich, glass- and gas-poor, porphyritic dacite (Pallister et al., 2008), which together with thermal infrared imagery (Snieder et al., 2006) indicates extrusion at temperatures below the rock's solidus, approximated to be 840–880 °C (Rutherford, 2008). Direct measurements by thermal imaging recorded temperatures of up to 600 °C at the surface (Scott et al., 2008), with gashes in the spines revealing internal temperatures of up to 730 °C (Vallance et al., 2008). Interstitial glass is present only in the dome rocks erupted during the first few months, then rapidly falls from >30% to <2% (Pallister et al., 2008). This may be accounted for by conduit residence time, during which the bulk of the dacitic magma had sufficient time to crystallise before reaching a depth of 1 km (Moran et al., 2008; Thelen et al., 2008), while the earliest magma was quenched faster as it pushed its way through the cool host rock and 150 m thick Crater Glacier (Vallance et al., 2010). Slowing of extrusion rate throughout the eruptive phase was contemporaneous with an increase in density (decrease in porosity), crystallinity and strength of the rocks (Smith et al., 2011).

Cashman et al. (2008) have characterised the spine surfaces early in the eruption through January 2006 and have documented variations between gouge, cataclasite and ultracataclasite. This gouge has been recreated experimentally by Kennedy et al. (2009). Experiments were performed at room temperature as it was considered that the time-scales in nature were too short for post-faulting modification or fault healing (Chester, 1994) which might result in increased frictional strength of a fault zone (Di Toro et al., 2006; Mizoguchi et al., 2006). Kennedy et al. (2009) established that fault products formed as a result of brittle deformation at the fault margin, with no indication of later annealing and no micro-structural evidence for high-temperature, solid-state crystal plasticity in the natural gouge samples (Cashman et al., 2008; Kennedy et al., 2009). Their work constrains deformation to post-crystallisation at a depth of less than 1 km. It is estimated that the fault products formed along 0.8–5 mm thick, sub-parallel, gouge-filled slip surfaces with strike lengths (*i.e.*, conduit circumference) of 98–190 m and displacements of ~5 mm as well as strain rates of approximately 5×10^{-2} s^{-1} to 5×10^{-1} s^{-1} (Kennedy et al., 2009). This could accommodate extrusions of up to 6 m per day contemporaneous with the microseismic "drumbeats".

During a field survey of the spines in August 2010, we identified a narrow zone of high-strain-rate structures on the extrusion margin of spine 7, which had not been observed on the previous spines. Here, we present a thorough characterisation of this structural zone to assess the temporal variability in erupted products and the conditions that may be sustained in volcanic conduits.