Earth and Planetary Science Letters 482 (2018) 171–180

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Hot pressing in conduit faults during lava dome extrusion: Insights from Mount St. Helens 2004–2008

Amy G. Ryan[a,*], Elizabeth A. Friedlander[a], James K. Russell[a], Michael J. Heap[b], Lori A. Kennedy[a]

[a] *Volcanology and Petrology Laboratory, Department of Earth and Ocean Sciences, University of British Columbia, 2020-2207 Main Mall, Vancouver, BC, V6T 1Z4, Canada*

[b] *Géophysique Expérimentale, Institut de Physique de Globe de Strasbourg (UMR 7516 CNRS, Université de Strasbourg/EOST), 5 rue René Descartes, 67084 Strasbourg cedex, France*

ARTICLE INFO

Article history:
Received 28 June 2017
Received in revised form 2 November 2017
Accepted 5 November 2017
Available online 16 November 2017
Editor: T.A. Mather

Keywords:
lava-dome
volcanic-fault-gouge
permeability
densification
sintering
hot-pressing

ABSTRACT

Rhyodacitic volcanoes such as Mount St. Helens (MSH), Soufrière Hills, Mount Unzen and Mount Pelée erupt spines mantled by layers of magma-derived cataclasite and fault gouge. MSH produced seven lava spines from 2004–2008 composed of low-porosity, compositionally uniform, crystalline dacite. Dome extrusion was attended by continuous 'drumbeat' seismicity, derived from faulting along the conduit margin at 0.5–1 km depth, and evidenced by the enveloping gouge layers. We describe the properties of the gouge-derived fault rocks, including laboratory measurements of porosity and permeability. The gouge varies from unconsolidated powder to lithified low-porosity low-permeability fault rocks. We reconstruct the subsurface ascent of the MSH magma using published field observations and create a model that reconciles the diverse properties of the gouge with conditions in the conduit during ascent (i.e. velocity, temperature). We show lithification of the gouge to be driven by 'hot pressing' processes, wherein the combination of elevated temperature, confining pressure and dwell-time cause densification and solid-state sintering of the comminuted, crystal-rich (glass-poor) gouge. The degree of gouge lithification corresponds with residence time in the conduit such that well-lithified materials reflect extended times in the subsurface due to slower ascent rates. With this insight, we suggest that gouge competence can be used as a first-order estimate of lava ascent rates. Furthermore we posit gouge lithification, which reduces porosity and permeability, inhibits volcanic outgassing thereby increasing the potential for explosive events at spine-producing volcanoes.

1. Introduction

The wide range of eruption styles and resulting landforms associated with the effusive eruption of rhyodacitic magma are an expression of magma rheology and eruptive flux. This is particularly true for the diverse array of morphologies presented by lava domes (Fink and Griffiths, 1998; Sparks et al., 2000; Watts et al., 2002; Cashman et al., 2008; Heap et al., 2016). An end-member of rhyodacitic lava domes that has received much attention in recent years are the spectacular lava spines observed at Mount Unzen, Japan (1990–1995; Nakada and Motomura, 1999; Nakada et al., 1999), Soufrière Hills volcano, Montserrat (1995–2003 and 2005–2013; Watts et al., 2002), and Mount St. Helens (MSH), Washington, USA (2004–2008; Iverson et al., 2006; Cashman et al., 2008).

These spines of lava share a number of features. First, the rocks that form the spines are highly crystallized, typically featuring high phenocryst contents and a microlitic groundmass (Nakada and Motomura, 1999; Sparks et al., 2000; Pallister et al., 2008; Cashman et al., 2008; Cordonnier et al., 2009). Groundmass glass (quenched rhyolitic melt) is subordinate (<15 vol%) and can be as low as <2 vol% (Sparks et al., 2000; Watts et al., 2002; Smith et al., 2011). Second, the spine-forming lava is typically dense – fractional porosities of extruded spine lavas are often measured to be less than 0.1 (Cashman et al., 2008; Cordonnier et al., 2009; Kennedy et al., 2009; Gaunt et al., 2014; Heap et al., 2016). Third, lava spines erupt at low extrusion rates (0.25–2 $m^3\,s^{-1}$; Nakada et al., 1999; Watts et al., 2002; Cashman et al., 2008; Holland et al., 2011) leading to low eruption temperatures and high degrees of crystallinity (i.e. low melt fraction) and, thus, high bulk viscosities (10^9 to 10^{14} Pa s; Nakada and Motomura, 1999; Sparks et al., 2000; Cordonnier et al., 2009; Holland et al., 2011). Indeed, instances of spine formation are restricted to high vis-

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* Corresponding author.
E-mail address: aryan@eoas.ubc.ca (A.G. Ryan).

https://doi.org/10.1016/j.epsl.2017.11.010

Table 1
Surface observations of the 2004–2008 eruption at Mount St. Helens, including: date range for each event, onset day (t), duration (Δt; days), volumetric (Q; $\mathrm{m^3\,s^{-1}}$) and linear (U; $\mathrm{m\,d^{-1}}$) extrusion rates and spine volume (V; $\times 10^6$ $\mathrm{m^3}$) (Vallance et al., 2008; Schilling et al., 2008). We include calculated spine volumes (V_i; $\times 10^6$ $\mathrm{m^3}$) and lengths (L_i; m), and the width of the fault zones occupied by gouge-derived material (w; m), measured in August 2010.

Event	Date[a]	t	Δt	Q	U	V[d]	V_i[e]	L_i[e]	w
Pre-seismicity	Sep 23–30 2004	0	8	–	–	–	–	–	–
Vent clearing	Oct 1–10 2004	8	10	7–12	>10	10	8.2 ± 2.2	261	–
Spine 1	Oct 11–15 2004	18	5	2–3	15–20	2	1.1 ± 0.2	34	–
Spine 2	Oct 15–24 2004	23	9	3	25	4	2.3	74	–
Spine 3	Oct 25–Dec 18 2004	32	55	4–6	8–11	21	23.8 ± 4.7	756	–
Spine 4	Dec 19 2004–Apr 9 2005	87	112	1.5–2.5	5–8	18	19.4 ± 4.8	616	0.2–2.6
Spine 5	Apr 10–Jul 31 2005	199	113	1–1.5	3–6	15	12.2 ± 2.4	388	1–1.5
Spine 6	Aug 1–Oct 9 2005	312	70	1.5–2	3–4	8	10.6 ± 1.5	337	–
Spine 7	Oct 10 2005–Jul 31 2007[b]	382	660	0.5–1	0.5–2[c]	25[d]	42.8 ± 14.3	1361	0.03–0.6
Endogenous growth	Aug 1 2007–Jan 27 2008[c]	1042	180	–	–				–
Total						93 ± 4[d]	112 ± 28	3829	

[a] Transition periods included in duration of the following spine.

[b] Approximate date for the end of spine 7 extrusion inferred from 2004–2008 time lapse videos for dome growth and crater glacier advance (https://volcanoes.usgs.gov/volcanoes/st_helens/multimedia_videos.html).

[c] End date for eruption, and minimum extrusion rate for spine 7 from the Global Volcanism Program bulletins.

[d] Total volume from Mastin et al. (2009); volume of spine 7 by subtraction.

[e] $V_i = (Q_i \Delta t_i)$; $L_i = (Q_i \Delta t_i)/(\pi(100)^2)$ where 100 m is the radius of the conduit (Iverson et al., 2006).

cosity magmas (andesite to dacite). Lastly, and most pertinent to this study, extruded lava spines, including those erupted at MSH, Soufrière Hills volcano, Mount Unzen, Mount Usu (Japan) and Mount Pelée (Martinique), commonly feature smooth or striated surfaces (Minakami et al., 1951; Fink and Griffiths, 1998; Sparks et al., 2000; Iverson et al., 2006; Cashman et al., 2008; Pallister et al., 2013) comprising a cm to m thick carapace of finely comminuted magma.

The carapace material is fault gouge formed by brittle deformation at the conduit–wall rock interface, where shear stresses are greatest (Sparks et al., 2000; Cashman et al., 2008; Kennedy et al., 2009; Kendrick et al., 2012; Hornby et al., 2015). Small, rapid slip events at this interface create a cylindrical fault zone along the outer margins of the highly viscous, rising magma, and convert the crystallized lava into a fine-grained fault gouge (e.g., Nakada and Motomura, 1999; Watts et al., 2002; Iverson et al., 2006; Neuberg et al., 2006; Pallister et al., 2008; Cashman et al., 2008; Kennedy et al., 2009; Kennedy and Russell, 2012; Gaunt et al., 2014; Kendrick et al., 2014; Hornby et al., 2015; Lamb et al., 2015). Evidence for these slip events is provided by the shallow (depths of 1 to 0.5 km) ‘drumbeat’ seismicity frequently recorded during spine-forming eruptions (Iverson et al., 2006; Moran et al., 2008a; Umakoshi et al., 2008; Pallister et al., 2013; Lamb et al., 2015; Hornby et al., 2015). Of interest, the extruded fault gouge material is extremely variable in physical and textural properties, ranging from unconsolidated powder to dense lithified fault rock (Minakami et al., 1951; Cashman et al., 2008; Kendrick et al., 2012; Pallister et al., 2013; Hornby et al., 2015).

Our question is: how does the conduit fault gouge lithify so effectively within the short timescales the shallow depths of origin imply? The process operates rapidly on essentially crystalline material (i.e. little to no glass/melt) even at moderate volcanic temperatures (<750 °C; Vallance et al., 2008). The MSH 2004–2008 spine-forming eruptions offer a singular opportunity to address this question because of the extensive array of associated geological observations and geophysical data. We use new laboratory measurements of porosity and permeability on samples of gouge rocks from three different spines at MSH to quantify the extent of lithification. We then use the observations from the MSH eruptions to reconstruct the ascent and thermal history of the individual magma packets that fed each of the seven lava spines. The reconstructions constrain the time–temperature–pressure window for the transformation processes that convert the fault gouge into competent, low-porosity and low-permeability fault rocks (i.e. lithification). Our analysis suggests that hot pressing, similar to that used commercially to produce ceramics and semi-conductors, drives lithification of the volcanic fault gouge associated with lava spine-producing volcanoes. This result is notable because it indicates there is an undiscovered lithification mechanism operating within the upper conduit during spine-producing eruptions that, significantly, does not require the presence of melt or the precipitation of new mineral phases.

2. A case study: Properties of MSH gouge

From 2004 to 2008 MSH produced seven discrete lava spines, each comprising a core of low-porosity dacite enveloped by a carapace of variably indurated fault gouge (Iverson et al., 2006; Cashman et al., 2008; Kennedy et al., 2009; Kendrick et al., 2012, 2014). Prior studies concluded that the magma crystallized and solidified at ∼1 km depth (Iverson et al., 2006; Pallister et al., 2008; Cashman et al., 2008) and then was pushed to the surface along cylindrical, conduit wall-parallel, fault zones. Brittle deformation along these faults resulted in the production of fine-grained, comminuted gouge from the solidified, crystal-rich, ascending dacite. Rhythmic seismicity (i.e. ‘drumbeat’ seismicity) was observed throughout the MSH eruption although the seismic energy released decreased with time (e.g., Iverson et al., 2006; Moran et al., 2008a) perhaps reflecting a decrease in ascent rate as the eruption waned. Previous workers interpreted the microseismic events as stick-slip events localized in the gouge along the conduit wall (Iverson et al., 2006; Cashman et al., 2008; Pallister et al., 2013). In contrast, we suggest the seismicity derives from relatively high stress drop events related dominantly to the production of gouge from the crystallized dacite magma (i.e., Kennedy et al., 2009; Kennedy and Russell, 2012). There were also low levels of magmatic outgassing measured throughout the eruption (Gerlach et al., 2008) focused along the conduit parallel faults (Rowe et al., 2008).

2.1. Textural organization, granulometry and mineralogy

The nature and properties of the enveloping fault gouge are well described in the literature, with a particular focus on the carapaces at spines 4 and 7 (Cashman et al., 2008; Pallister et al., 2008; Kennedy et al., 2009; Kendrick et al., 2012; Gaunt et al., 2014). Table 1 reports our field measurements of the thickness of the fault gouge carapaces. The gouge material encasing spines 4 and 5 is 1 to 3 m thick whereas the gouge is considerably thinner (0.03–0.6 m) at spine 7 (Table 1). The conduit-parallel fault