Journal of Volcanology and Geothermal Research 328 (2016) 159–177

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Mechanical behaviour of dacite from Mount St. Helens (USA): A link between porosity and lava dome extrusion mechanism (dome or spine)?

M.J. Heap [a,*], J.K. Russell [b], L.A. Kennedy [b]

[a] Géophysique Expérimentale, Institut de Physique de Globe de Strasbourg (IPGS), École et Observatoire des Sciences de la Terre (EOST), Université de Strasbourg (UMR 7516 CNRS), 5 rue René Descartes, 67084 Strasbourg, France
[b] Volcanology and Petrology Laboratory, Department of Earth and Ocean Sciences, University of British Columbia, 6339 Stores Road, Vancouver, V6T 1Z4, British Columbia, Canada

ARTICLE INFO

Article history:
Received 8 July 2016
Received in revised form 28 October 2016
Accepted 28 October 2016
Available online 30 October 2016

Keywords:
Porosity
Permeability
Strength
Brittle
Ductile
Triaxial

ABSTRACT

There is a rich diversity in lava dome morphology, from blocky domes and lobes to imposing spine and whaleback structures. The latter extrude via seismically active, gouge-rich conduit-margin faults, a manifestation of a brittle failure mode. Brittle versus ductile behaviour in volcanic rocks is known to be porosity dependent, and therefore offers a tantalising link between the properties of the material near the conduit margin and the extrusion mechanism (dome or spine). We test this hypothesis by complementing published data on the mechanical behaviour of dacites from the 2004–2008 spine-forming eruption at Mount St. Helens (MSH) with new data on dacite lavas collected from the 1980 dome. The 1980 dacite samples were deformed at room temperature under a range of pressures (i.e., depths) to investigate their mechanical behaviour and failure mode (brittle or ductile). Low-porosity dacite (porosity ~0.19) is brittle up to an effective pressure of 30 MPa (depth ~1 km) and is ductile at 40 MPa (depth ~1.5 km). High-porosity dacite (porosity ~0.32) is ductile above an effective pressure of 5 MPa (depth ~200 m). Samples deformed in the brittle regime show well-developed (~1 mm) shear fracture zones comprising broken glass and crystal fragments. Samples deformed in the ductile regime feature anastomosing bands of collapsed pores. The combined dataset is used to explore the influence of strain rate, temperature, and porosity on the mechanical behaviour and failure mode of dacite. A decrease in strain rate does not influence the strength of dacite at low temperature, but reduces strength at high temperature (850 °C). Due to the extremely low glass content of these materials, such weakening is attributed to the increased efficiency of subcritical crack growth at high temperature. However, when strain rate is kept constant, temperature does not significant impact strength reflecting the highly crystallised nature of dacite from MSH. Dacite from the 2004–2008 eruption is stronger than 1980 dome material and remains brittle even at high effective pressures, a consequence of their low preserved porosities. Only the porous (porosity ~0.32) 1980 dome material deformed in a ductile manner (i.e., no macroscopic shear fracture) at effective pressures relevant for edifice deformation. Spine formation typically involves the extrusion of low-porosity material along faults that envelop the magma-filled conduit (i.e., brittle deformation), suggesting that the extrusion mechanism (dome or spine) may be a consequence of slow ascent rates and efficient pre-eruptive outgassing. Well-outgassed, low-porosity (slow ascent rate) materials favour a brittle mode of failure promoting spine extrusion, while poorly-outgassed, high-porosity (fast ascent rate) materials result in blocky domes or lobes. A crystal content-porosity map for brittle (spine) versus ductile (blocky dome) behaviour demonstrates that the window for brittle deformation is small and offers an explanation as to why spine and whaleback structures are relatively rare in nature.

1. Introduction

Lava dome morphology is richly diverse (Watts et al., 2002; Calder et al., 2015). Although most lava dome forming eruptions result in blocky domes and lobes, there are curious and spectacular instances of dense spines that extrude via seismically active, gouge-rich conduit-margin faults (e.g., Nakada et al., 1999; Watts et al., 2002; Melnik and Sparks, 2002; Iverson et al., 2006; Pallister et al., 2008; Cashman et al., 2008; Kennedy and Russell, 2012; Gaunt et al., 2014; Kendrick et al., 2014; Hornby et al., 2015; Lamb et al., 2015). Recent examples include the 1990–1995 activity at Mount Unzen (Kyūshū, Japan) that saw the growth of a spine over 40 m in height (Nakada et al., 1999), the growth of spines or "whalebacks" during the 2004–2008 eruptive activity at Mount St. Helens (MSH; Washington, USA) (Iverson et al., 2006), and the extrusion of "megaspines" during the 1996 activity at Soufrière Hills volcano (Montserrat) (Watts et al., 2002). The conduit-margin fractures at the conduit-wall rock interface are a manifestation of a

* Corresponding author.
E-mail address: heap@unistra.fr (M.J. Heap).

http://dx.doi.org/10.1016/j.jvolgeores.2016.10.015
0377-0273/

brittle deformation mode. The porosity dependence of brittle versus ductile behaviour in volcanic rocks (Heap et al., 2015a; Zhu et al., 2016) therefore offers a tantalising link between extrusion mechanism (dome or spine) and the porosity of the material at the conduit-wall rock interface. While low-porosity volcanic rocks generally behave in a brittle manner at low and high pressure (or depth), high-porosity rocks can be brittle at low pressure and ductile at high pressure (or depth) (Heap et al., 2015a; Zhu et al., 2016).

The ability of ascending magma to outgas exsolving volatiles, and the time available for such outgassing, likely play key roles in the porosity present in magma and preserved in volcanic rock (e.g., Watts et al., 2002; Melnik and Sparks, 2002). Viewed simplistically, moderate to fast ascending magmas have little time for outgassing, cooling, and crystallisation. These magmas reach the surface as hot, high-porosity, melt-bubble mixtures with subordinate crystal contents; brittle behaviour in these lavas is therefore unlikely (we further note that an increase in the crystal content of magma increases the likelihood of brittle behaviour; Cordonnier et al., 2012). By contrast, slow ascending magmas have a greater opportunity to outgas, and allow more time for cooling to their appropriate glass transition temperature (*Tg*) and/or for crystallisation of the melt prior to extrusion (e.g., Cashman et al., 2008). The extruded materials in this case will be low-porosity, highly crystallised lava or lava that is near or below *Tg* and, as a result, brittle behaviour is more probable.

To explore the porosity dependence of the extrusion mechanism—dome or spine—we complement pre-existing data on the physical properties (e.g., porosity and permeability) and mechanical behaviour of dacites from the 2004–2008 spine-forming eruption at MSH (Klug and Cashman, 1996; Kennedy et al., 2009; Smith et al., 2011; Kennedy and Russell, 2012; Kendrick et al., 2013; Gaunt et al., 2014, 2016) with new data on dacite lavas collected from the 1980 dome. We first characterised our samples in terms of their textural properties, porosity, permeability, and their porosity-permeability relationship. We then present results from room temperature triaxial experiments performed at different effective pressures (depths) in which we monitored porosity change and the output of acoustic emission energy during deformation. Post-deformation microstructural analysis was employed to understand the micromechanisms of deformation. The data compilation (i.e., published data from 2004–2008 spine-forming dacites and new data from 1980 dome-forming dacites) is used to explore porosity-permeability relationships and the range of mechanical behaviour and failure modes (brittle or ductile) to be expected of dacite as a function of its residual porosity, strain rate, and temperature. We use insight gleaned from these data to map out porosity-crystal (or glass/melt) content windows for spine versus blocky lava dome extrusion. We further anticipate that the physical and mechanical data compiled here will inform models of slope stability and outgassing at MSH and at other active dacitic volcanoes worldwide.

2. Mount St. Helens (MSH), Washington (USA)

Our principal goal is to present data that can inform on mechanisms of lava extrusion (spine versus blocky dome). We additionally consider our data on the mechanical and hydraulic properties of dacites relevant for models of outgassing and assessments of the structural stability of dacitic volcanoes worldwide. Eruptive activity at MSH, an active stratovolcano belonging to the Cascade volcanic arc of North America (located in Skamania County in Washington (USA); Fig. 1a), has recently produced episodes of dome-growth (1980–1986) and spine-growth (2004–2008) and therefore represents an ideal natural laboratory to undertake such a study.

The eruptive history of MSH has been divided into nine distinct periods: Ape Canyon, Cougar, Swift Creek, Smith Creek, Pine Creek, Castle Creek, Sugar Bowl, Kalama, and Goat Rocks (Lipman and Mullineaux, 1981). These periods are characterised by episodes of dome-building, explosive eruptions, pyroclastic flows, and lahars. The erupted products

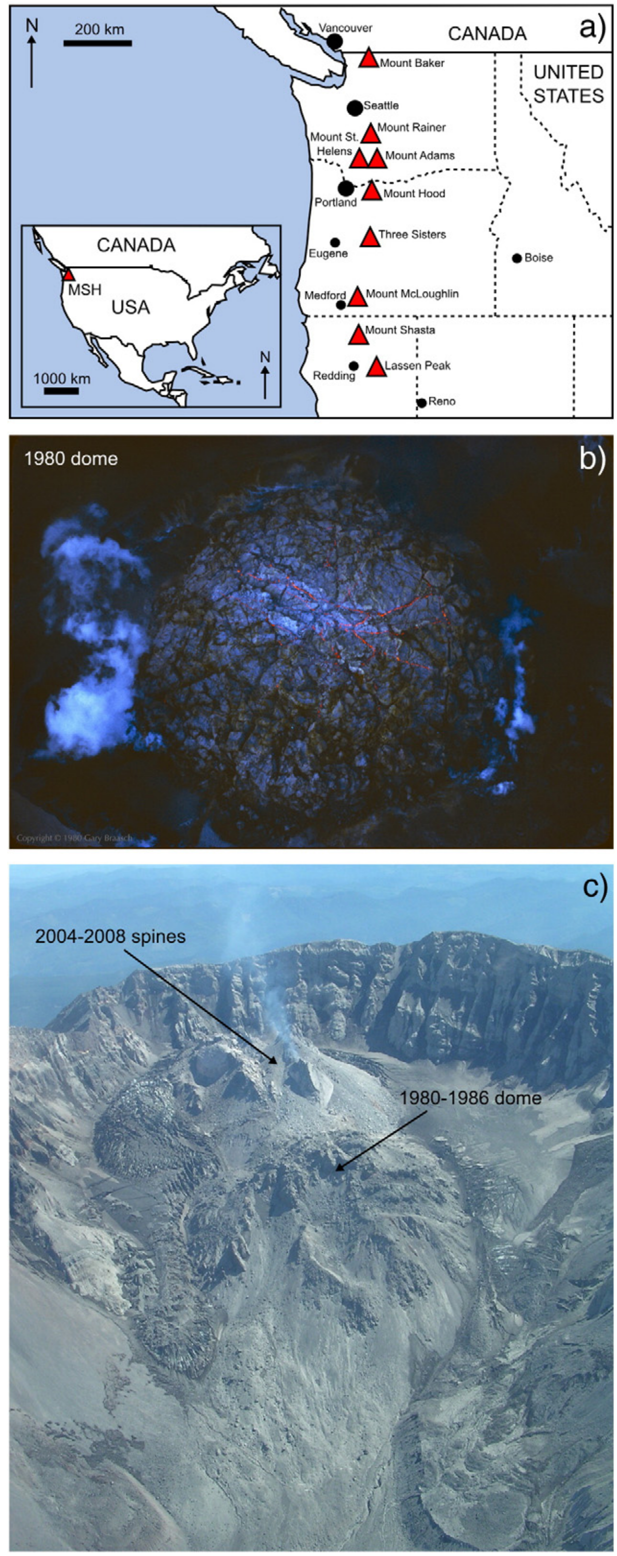

Fig. 1. Mount St. Helens (MSH). (a) Map showing the volcanoes of the Cascade Volcanic Arc of North America. Inset shows the location of MSH in North America. (b) Aerial view of the 1980 lava dome at MSH. Copyright © 1980 Gary Braasch Photography. Photograph used here with permission from Gary Braasch. (c) Aerial view of the crater at MSH (photograph taken September 2006; photo credit: Kelly Russell) showing the 1980–1986 domes and the spines of the 2004–2008 eruption.

are mainly dacite with subordinate andesite and basalt (e.g., Castle Creek eruptive period; Lipman and Mullineaux, 1981). MSH gained most of its attention and notoriety for the devastating eruption that