Pathways for degassing during the lava dome eruption of Mount St. Helens 2004–2008

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ABSTRACT

The ability of volatiles to escape rising magma regulates the explosivity of a volcanic system. During silicic lava dome eruptions, strain localization at the conduit margin occurs during magma ascent, creating a damage halo with implications for gas escape. Here we report the first systematic study of permeability network anisotropy across the marginal shear zone of the A.D. 2004–2008 lava dome at Mount St. Helens (Washington State, USA). The results show increasingly large permeability anisotropy of as much as four orders of magnitude (over ~4 m) moving from the interior of the spine through the damage halo. We find the permeability to be essentially isotropic in the spine interior but highly anisotropic in the damage zone and fault core. Our examination of the dome rocks reveals that the permeability anisotropy depends strongly on the presence of vertically oriented shear layers. Here we show that the rate of escape of volatiles will be several orders of magnitude higher vertically through a conduit margin shear zone than horizontally into the conduit wall.

INTRODUCTION

The presence of gas in magma ascending to the Earth's surface has a strong control on the timing and style of volcanic eruptions (Woods and Koyaguchi, 1994; Sparks, 1997). During ascent, decompression decreases the solubility of dissolved volatiles, which exsolve, forming a separate gas phase (e.g., Navon et al., 1998). The ability of these gases to escape the rising magma determines the explosivity of the volcanic system and depends strongly on both the supply rate of the magma (Nguyen et al., 2014) and the development of a permeable network within the magma (Sparks, 1997). As pressure decreases during ascent, gas bubbles expand and challenge the stability of the magma, which can result in explosive fragmentation (Alidibirov and Dingwell, 1996). However, nonexplosive fragmentation can also occur due to the non-Newtonian response of viscous silicic magma to flow-related strain at the conduit margins, leading to strain localization and failure (Gonnermann and Manga, 2003; Tuffen and Dingwell, 2005). Significant degassing is believed to occur in the upper kilometer of magmatic conduits (e.g., Westrich and Eichelberger, 1994). Thus, the explosive-effusive transition is intimately linked to degassing processes in the shallow conduit. In volcanoes where the magma supply rate varies little, as is the case for lava spine 4 at Mount St. Helens (Washington State, USA), such degassing is likely to depend primarily on the permeability of the magma. Permeable fracture networks can develop and allow the gas phase to escape vertically through the magma column (e.g., Holland et al., 2011; Schipper et al., 2013) or horizontally through the conduit walls (Stasiuk et al., 1996; Jaupart, 1998). Gases can also escape if the rate of exsolution is balanced by the flow of gas from bubble to bubble through the development of permeable foam (e.g., Eichelberger et al., 1986; Okumura et al., 2008).

The direction of gas flow is dependent on the architecture of the permeable porous network and the development of gas pressure gradients (Massol and Jaupart, 2009). There are two principal ways to create a permeable network: through the coalescence of bubbles either by expansion or elongation (Klug and Cashman, 1996; Okumura et al., 2008) or by the brittle rupture of magma due to an applied shear stress (Gonnermann and Manga, 2003). Previous permeability studies on volcanic rocks have focused on the porosity and permeability relationships of pumice and the products of other eruption styles, and only a fraction of these assess the anisotropy of these rocks.

It has been proposed that shear-induced fracturing at the conduit margins creates a damage halo, which acts as a permeable pathway for vertical gas escape (e.g., Holland et al., 2011; Schipper et al., 2013). Ring-shaped gas and ash venting events observed at Santiaguito volcano, Guatemala, have been attributed to this process (Bluth and Rose, 2004). The evaluation of the potential pathways for outgassing in volcanic conduits requires a systematic study of the permeability across the magmatic column. The recent eruptive phase at Mount St. Helens extruded lava spines, which provide a view of the magmatic structure in the upper conduit. Recent studies (Kendrick et al., 2012; Pallister et al., 2013) have detailed the structure of the damage halo and related conduit margin shear zone at Mount St. Helens. Here we describe the permeable network of this structure. In this paper we present steady-state flow permeability measurements of a suite of rocks collected from the margin of spine 4 in two perpendicular orientations (parallel and perpendicular in relation to the extrusion direction). An evaluation of the effects on gas escape is also discussed.

MOUNT ST. HELENS 2004–2008

Mount St. Helens is the most active volcano in the Cascade Range, with multiple phases of lava dome growth since 1981. During the 2004–2008 eruption, dacite magma was extruded almost continuously as a succession of seven lava spines (Pallister et al., 2013). The magma crystallized within 1 km below the vent (Pallister et al., 2008) and underwent intense strain localization, which took place at the conduit margins during ascent (Iverson et al., 2006). Of the seven spines extruded, spine 4 (~120 m in diameter, extruded between January and April 2005) was the most prominent. It formed a smooth "whaleback" (an intact smooth curved extrusion) that subsequently collapsed (Iverson et al., 2006) (Fig. 1A). Nearly continuous monitoring of the extrusion and collapse of the spines by the U.S. Geological Survey Cascades Volcano Observatory allowed the reconstruction of the pre-eruption geometry of the spine as a subvertical plug of magma spanning much of the volcanic conduit. During a field excursion in August 2010, we systematically collected samples from the spine interior to the surface of a collapsed section of spine 4 (Fig. 1B) and obtained a helicopter-dredged sample of fault gouge from the Cascades Volcano Observatory collection (Thornber et al., 2008). Samples collected in situ were oriented with respect to the extrusion direction. Paint markers that were applied to the newly extruded spine surface in 2005 were located during the field excursion, confirming the insignificant extent of postemplacement erosion.

SPINE 4 STRUCTURE AND ROCK MICROSTRUCTURE

Using field observations and scanning electron microscopy, Pallister et al. (2013) defined a pseudostratigraphy of the spine and marginal shear zone based on the observed damage and crack densities. Four different lithofacies were defined: massive dacite, sheared dacite, cataclastic breccia, and fault gouge. Figure 1B shows a representative section of the pseudostratigraphy (Pallister et al., 2013) from which our experimental samples were collected. The interior of spine 4 (Fig. 1) consists of generally massive but locally flow-banded, crystal-rich dacite containing ~65 wt%

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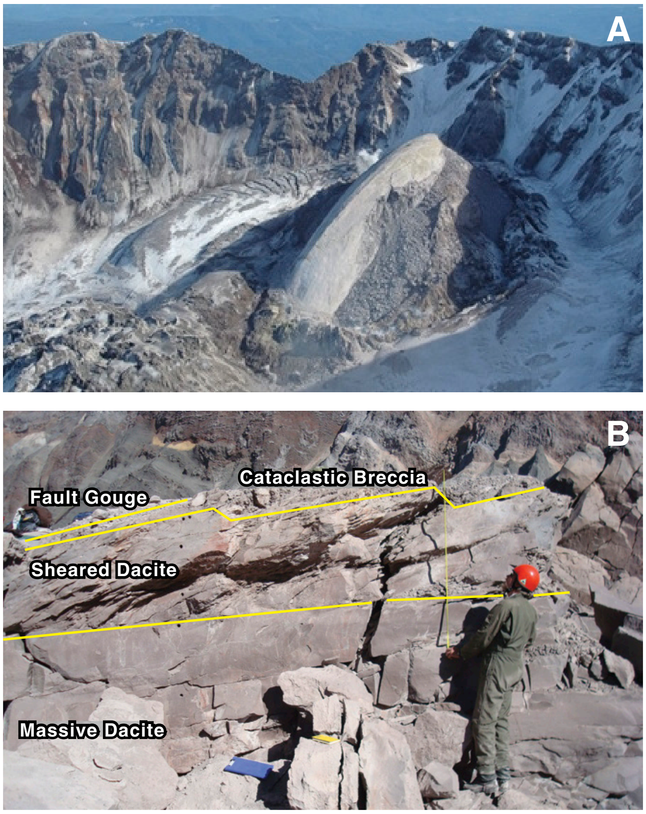

Figure 1. A: Mount St. Helens (Washington State, USA) lava dome spine 4 taken on 2 February 2005 from the northwest; recumbent "whaleback" spine (see text) is ~400 m long (photograph courtesy of S. Schilling, U.S. Geological Survey). B: Interior of collapsed spine 4 taken on 24 August 2010. The spine was extruded from the vent in a steep orientation, and then rotated to subhorizontal position during transport away from the vent. As a consequence, features shown as subhorizontal in this image were formerly subvertical in the subsurface (Pallister et al., 2013). Tape measure in photo is extended to 1.6 m.

SiO_2 and ~50 vol% phenocrysts of plagioclase, amphibole, pyroxene, and oxide minerals (termed massive dacite). Microlite crystallization accompanying final stages of ascent and degassing increased the total crystal content to close to 100% (Pallister et al., 2008). The spine is mantled by fault rocks as thick as ~4 m. The marginal structure comprises two zones: from the interior outward, (1) a damage zone composed of sheared dacite exhibiting widely spaced subhorizontal fractures and thousands of closely spaced decimeter- to meter-length Riedel shears and a zone of cataclastic breccia, also containing Riedel shears, and (2) a fault core of variable thickness (to ~2 m) consisting of fault gouge (Fig. 1B). The fault gouge contains multiple ultracataclasite layers parallel to the direction of extrusion (Pallister et al., 2013). The fault structure has been described as similar to that of tectonic faults (Cashman et al., 2008; Kendrick et al., 2012), and has been noted for other fault systems in silicic conduits (Tuffen and Dingwell, 2005).

The suite of samples collected for this study spans a distance of ~10 m from the spine margin shear zone into the spine interior and includes samples from all of the defined zones in the pseudostratigraphy. Samples from the marginal shear zone of spine 4 all have similar chemical compositions because they are all derived from the same starting material, but they have greatly differing microstructures. Our massive dacite from the interior of the spine is a crystal-rich dacite with a pervasive microfracture network that dominates the porosity, as shown in Figure 2A. The microfractures have no preferred orientation, and vesicles are present but make up a minor proportion of the porosity. The first evidence of brittle breakage associated with the upward movement of the magma is manifested as throughgoing fractures in our sample identified as sheared dacite (Fig. 2B). Strain appears to be initially partitioned into the groundmass, leaving the phenocrysts mainly intact. Fractures in the groundmass have begun to connect, creating a macrofracture network aligned subvertically, which increases the porosity. Exterior to the sheared dacite, a cataclastic breccia with a fragmental, brittle character formed. Granular flow features are present and there is evidence of grain rotation and shattered phenocrysts, producing a new aligned and connected porosity (Fig. 2C). In the fault core, comminution of grains through shearing produced a fault gouge (Cashman et al., 2008). In the extreme case of shearing, anastomosing slickensided shear layers 1–3 mm thick were produced within the gouge. The shear layers are parallel to the extrusion direction. They are composed of ultracataclasite in which there was grain-size reduction to <1 µm (Fig. 2D).

EXPERIMENTAL FLUID FLOW

Results from a series of steady-state permeability measurements for an effective pressure of 5 MPa are shown in Figure 3. The results are for five samples that span the margin of spine 4 and include data for both parallel and perpendicular orientations with respect to the extrusion direction. Our experiments were done at room temperature, as our focus has been on conditions appropriate for a solidified magmatic plug and where the influence of temperature (below 600 °C) on magma fracture is weak (Tuffen et al., 2008; Smith et al., 2011). Permeabilities of all specimens from the spine interior were in the same range and thus virtually isotropic. In the damage zone, the horizontal permeability is approximately the same as in the spine interior dacite. There is strong permeability anisotropy in this suite of samples; the vertical permeability increases by nearly two orders of magnitude. The strongest permeability anisotropy is observed in the fault gouge, reaching nearly four orders of magnitude greater in the vertical direction than in the horizontal direction. The permeability trends remained similar over a range of effective pressures from 5 to 30 MPa (see the GSA Data Repository[1]). The porosity of the rocks increases outward across the spine and displays a kink, with an abrupt increase between the cataclastic breccia and the sheared dacite (Fig. 3).

DISCUSSION

This is the first systematic study of permeability anisotropy through a volcanic conduit margin shear zone. Vertical permeability increases by two orders of magnitude in the marginal shear zone, consistent with increasing brittle deformation and the development of connected shear fractures oriented parallel to the conduit wall (Pallister et al., 2013). These shear fracture networks allow fluids to move vertically through the magma column (Holland et al., 2011; Schipper et al., 2013). We attribute the sharp decrease in horizontal permeability in the fault gouge to the presence of the vertical ultracataclasite shear layers (Fig. 3). The relatively low permeability and low anisotropy of the fracture network in the rocks from the spine interior suggest that the magnitude and direction of gas flow is controlled solely by pressure gradients (Sparks, 1997; Massol and Jaupart, 2009). In contrast, the extremely low horizontal permeability of the ultracataclasite in the fault gouge prevents lateral outgassing even at high horizontal pressure gradients. The permeability of the conduit wall rocks was also measured (see the Data Repository). However, this is likely of little consequence in this case, because the low horizontal permeability of the fault gouge prevents the lateral movement of fluids into the wall rocks. Instead, the highly anisotropic nature of the permeable network in the rocks near the conduit margin channels fluid and gas ascent vertically toward the low-pressure regime at the surface.

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[1]GSA Data Repository item 2014337, results at elevated confining pressure, wall-rock permeabilities, and gas flux calculations, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

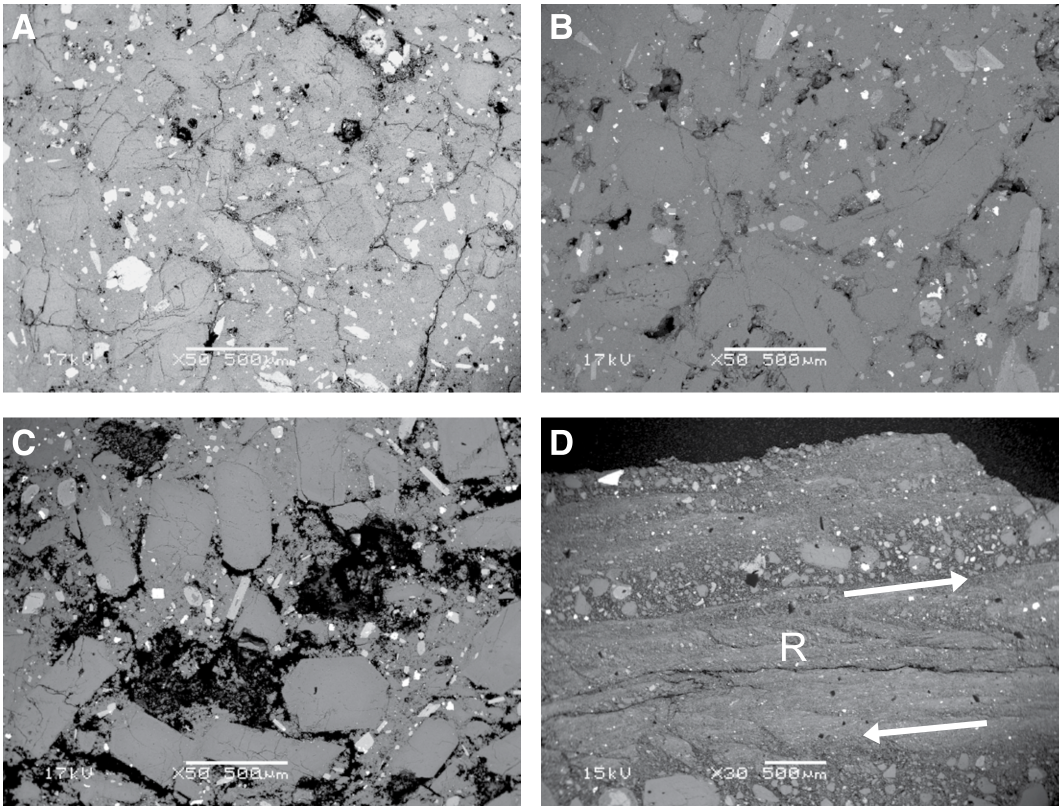

Figure 2. Scanning electron microscope backscatter photomicrographs. A: Intact dacite showing pervasive microfracture network. B: Sheared dacite showing brittle breakage and strain partitioned within the groundmass, leaving phenocrysts intact. C: Cataclastic breccia showing granular flow, comminution features, and phenocryst rotation. D: Fault gouge showing ultracataclasite shear layer containing micro-Riedel shears (R) at its margin. Arrows indicate direction of shear.

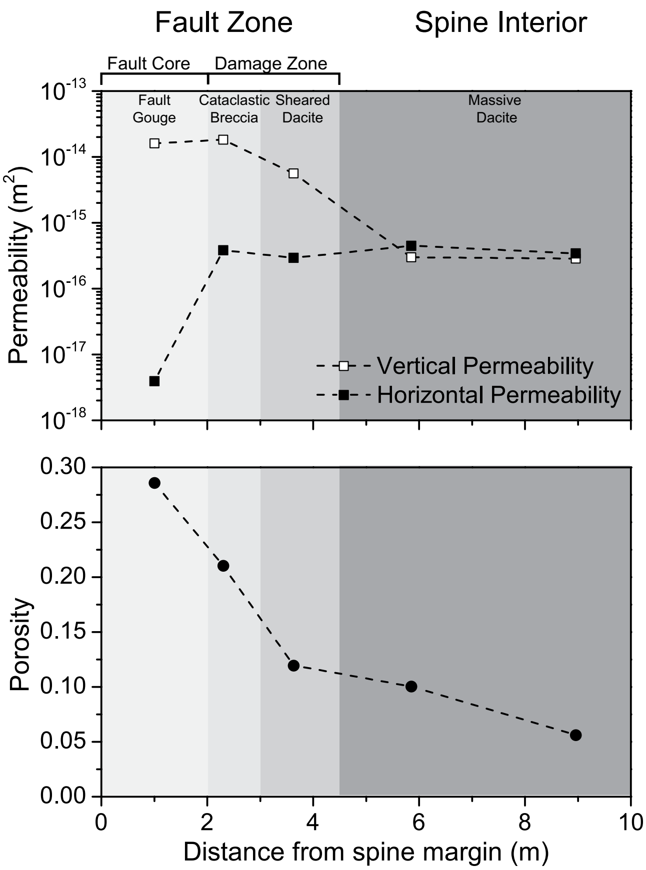

Figure 3. Measurements of permeability and porosity for the different lithofacies (shown as shaded bands) of spine 4 plotted against the distance from the spine margin. Permeability measurements were made on samples oriented both parallel (subvertical, open symbols) and perpendicular (subhorizontal, closed symbols) to the conduit wall.

There is a lack of permeability data from similar rocks, so direct comparison to other conduit rocks is not possible. However, permeability anisotropy studies have been conducted on tube pumices, which show preferential permeable flow along elongate pores (e.g., Bouvet de Maisonneuve et al., 2009; Okumura et al., 2008). Microstructural analysis constrains the development of such porous structures to simple shear in the magma near conduit margins (e.g., Bouvet de Maisonneuve et al., 2009). Consequently, different modes of vertical fluid and gas ascent are indicated, depending on the properties of the magma and the related mechanism of shear. In contrast to the relatively low viscosity and gas-rich magmas that produce tube pumice, dacite from Mount St. Helens was degassed and had effectively solidified before shearing took place (Pallister et al., 2013). This indicates that fracturing and deformation may be more important than vesicle elongation in creating pathways for gas escape in strongly degassed and highly viscous magmas, which are erupted passively as lava spines and domes.

Our results are consistent with field observations of gas escape, principally from a damage halo documented at Mount St. Helens (Pallister et al., 2013), and from other volcanoes such as Santiaguito (Bluth and Rose, 2004). We suggest that in the upper conduit of spine- and dome-forming eruptions, the vertical volatile volumetric flow rate will be orders of magnitude greater than the horizontal rate (see the Data Repository). Our data indicate that in these situations, volatile flow is dominantly partitioned vertically within the marginal shear zone, consistent with the spine margin location of gas and ash venting during the eruption (Cashman et al., 2008; Pallister et al., 2013). Rheological studies of dome magma showed that by mapping and modeling crack density in experimentally deformed magmas, brittle damage is increased near the conduit margin due to strain localization and high stresses (Lavallee et al., 2013). With an increase in applied stress, fractures develop subparallel to the principal stress, thereby increasing the anisotropy of the permeable porous network. Our study is consistent with such findings, and demonstrates how the development of permeable shear fractures and consequent escape of gas therefore lessens the likelihood of an explosive eruption (see Mueller et al., 2008). The healing of these fracture zones would encourage volatile retention and cyclic explosivity, while the absence of melt in shear zones will delay, and may even prevent, the healing of fractures (Tuffen and Dingwell, 2005; Schipper et al., 2013). This is especially the case for the highly crystalline, cataclastic fault rocks at Mount St. Helens that provide long-lived degassing pathways and therefore potentially reduce the amount of gas that is retained in the magma column.

APPENDIX: METHODS

We measured the connected porosity and permeability of the four lithofacies from spine 4 in a high-pressure, steady-state permeameter (Benson et al., 2005). Test specimens 25 mm in diameter and to 62.5 mm in length, cored from the collected blocks, oriented either parallel or perpendicular to the extrusion direction, were first air-dried, and then water-saturated under vacuum to determine their porosity. The specimens were then jacketed in a rubber sleeve and placed inside the permeameter between stainless steel end caps. Fixed effective pressures between 5.0 and 35.0 MPa were then applied. Pore fluid (pressurized water) was driven through the specimen at a fixed mean pressure of 5.0 MPa and a constant differential pressure of 0.5 MPa across the specimen length. Once steady-state flow was achieved, permeability was calculated from the pressure gradient, fluid viscosity, and measured flow rate by direct application of Darcy's law. Experimental errors for the permeability and porosity measurements were calculated and were less than ±4% and ±0.2%, respectively, for all samples. Two or more repeat tests on each lithofacies were conducted to check for repeatability.

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