Journal of Volcanology and Geothermal Research 292 (2015) 29–40

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Rates of water exsolution and magma ascent inferred from microstructures and chemical analyses of the Tokachi–Ishizawa obsidian lava, Shirataki, northern Hokkaido, Japan

Kyohei Sano [a,*], Keiji Wada [a], Eiichi Sato [b]

[a] Earth Science Laboratory, Course of Subjects Education, Graduate School of Education, Hokkaido University of Education at Asahikawa, Hokumon 9, Asahikawa, Hokkaido 070-8621, Japan
[b] Institute for Promotion of Higher Education, Kobe University, Tsurukabuto 1-2-1, Nada, Kobe 657-8501, Japan

ARTICLE INFO

Article history:
Received 10 April 2014
Accepted 14 November 2014
Available online 28 January 2015

Keywords:
Textural analysis
Obsidian–rhyolite lava flow
Magma ascent rate
Outgassing mechanism

ABSTRACT

Very few quantitative textural data exist for viscous obsidian lava eruptions, and it is still unclear from the mechanical behavior of ascending magmas if outgassing is controlled dominantly by brittle or ductile deformation. In order to obtain insights into how degassing and ascent proceed in such highly viscous magmas, we conducted textural and chemical analyses of the Tokachi–Ishizawa (TI) obsidian lava, in the Shirataki rhyolite volcanic area, northern Hokkaido, Japan, and estimated the water exsolution rate and ascent rate. The storage conditions of the TI lava are estimated from the Rhyolite-MELTS program as $T = 840$–860 °C and $P = 50$ MPa using the mineral assemblages and the chemical compositions of plagioclase phenocrysts and glass. To estimate the magma ascent rate, we measured the length, width, and number of oxide microlites using three-dimensional techniques. Textural analysis indicates that the microlite number densities (Nv [number/m^3]) of oxide microlites in TI lava samples are 2.1×10^{13} to 1.4×10^{14}, which correspond to water exsolution rates of 3.5×10^{-9} to 1.7×10^{-8} wt.%/s and ascent rates of 1.7×10^{-6} to 1.1×10^{-5} m/s. Together with an estimate of viscosity, the inferred ascent velocities allow us to examine the mechanical behavior of the magma in the conduit. We conclude that the development of permeability leading to outgassing is controlled by ductile deformation rather than brittle fracturing.

1. Introduction

Silicic volcanism ranges from explosive to effusive, with the range of viscosity and diffusivity being strongly controlled by the water and phenocryst contents of the magma. Studies of silicic volcanism show that water exsolution and outgassing are the dominant processes that determine the eruption style of viscous magmas (Eichelberger et al., 1986; Woods and Koyaguchi, 1994; Gonnermann and Manga, 2003; Castro and Dingwell, 2009). The efficiency of outgassing is determined by the competition between the magma ascent rate and the rate at which volatiles can escape from the rising magma (e.g., Jaupart and Allègre, 1991; Woods and Koyaguchi, 1994). Petrological and geochemical studies have provided constraints for the water exsolution and ascent rates of viscous magmas. At Big Glass Mountain, California, USA, Castro et al. (2005) estimated the water exsolution rate of obsidian dome eruptions as 6×10^{-8} to 8×10^{-7} wt.%/s based on the diffusion profiles of H_2O from glassy to vesicular parts in the lava. Castro and Dingwell (2009) conducted experiments in which they reproduced the plagioclase rim growth in samples from Chaitén volcano, Chile. Comparing these experimental overgrowth textures with natural samples, they estimated the decompression rate of viscous magmas to be -1.1×10^{-2} MPa/s, and raised the possibility that viscous magmas are able to rise from their storage zones to surface in a few hours.

Three main controls on outgassing have been proposed: (1) ascent of bubbles in less viscous magma, as observed in Strombolian and Hawaiian eruptions (Vergniolle and Jaupart, 1990; Parfitt, 2004); (2) permeable flow through interconnected bubble networks (e.g., Eichelberger et al., 1986); and (3) flow through brittle fractures (Tuffen et al., 2003). For viscous magmas, interconnected bubble networks and brittle fractures are thought to be dominant pathways for outgassing.

Many studies have examined obsidian lava flows in order to explain the role of various processes, such as water exsolution rates, outgassing and emplacement, both in the volcanic conduit and on the surface (Fink, 1983; Eichelberger et al., 1986; Swanson et al., 1989; Fink et al., 1992; Stevenson et al., 1994; Manga, 1998; Stevenson et al., 2001; Castro et al., 2002; Rust et al., 2003; Tuffen et al., 2003; Castro et al., 2005; Furukawa et al., 2010; Cabrera et al., 2011; Castro et al., 2013; Schipper et al., 2013; Waters and Lange, 2013). Fink (1983) described the structure of obsidian lava, and revealed that deformation processes disrupt the initial layering of the lava flow as it advances. Manga (1998) measured the orientation of microlites in obsidian and suggested that these microlites record the flow dynamics during emplacement. Rust et al. (2003) determined shear rates and stress from bubble shapes

* Corresponding author at: Department of Earth and Planetary Sciences, Graduate School of Sciences, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan. Tel.: +81 92 642 2650; fax: +81 92 642 2684.
E-mail address: kyohei.sano.069@s.kyushu-u.ac.jp (K. Sano).

http://dx.doi.org/10.1016/j.jvolgeores.2014.11.015
0377-0273/

and orientations, and spherulites in obsidian glass have been analyzed to estimate their thermal history during crystallization (Castro et al., 2008; Watkins et al., 2009). However, detailed analyses of microlites are rare because effusive obsidian lava eruptions are hardly ever observed (e.g., Schipper et al., 2013) and few outcrops expose the interior structure of these lavas, although Befus et al. (2014) analyzed samples from 10 locations across an obsidian dome at the Douglas Knob, Yellowstone volcanic field.

Some drilling projects have described the structure of obsidian lava. For example, Eichelberger et al. (1985, 1986) and Swanson et al. (1989) described the structure of Inyo Domes, California, USA, and Manley and Fink (1987) compared the textural zonation in the Inyo Obsidian Dome, the 140 ka Banco Bonito flow in New Mexico, and the 8 Ma domes in Arizona. In most of these studies no quantitative data are reported, although macroscopic textures such as vesicularity and spherulites are described. Although some studies have reported the size distribution of microlites in obsidian (Swanson et al., 1989; Castro and Mercer, 2004; Castro and Gardner, 2008), these studies did not address the water exsolution rate and outgassing processes from microlite analysis in a single obsidian lava flow.

Textural analysis, which can be used to constrain the processes controlling ascent and water exsolution in magmas of various compositions (Cashman, 1992; Klug and Cashman, 1994; Noguchi et al., 2006, 2008), may also give insights into the process of outgassing because ascent velocity is one of the major controlling factors on outgassing efficiency, together with the formation of permeability. At Cordón Caulle, Chile, Schipper et al. (2013) reported direct observations of hybrid explosive–effusive eruptive activity of silicic magma. They suggested that tube-like textures in silicic magma are evidence of the ductile development of permeability extending up to 1.5 km into the subsurface conduit, and that brittle processes, which ejected both bubbly and dense magma, occur in the very shallow vent region. However, few studies contain quantitative textural data relating to the mechanical behavior and ascent rates for viscous obsidian lava eruptions, meaning that the question of whether the dominant outgassing process is brittle or ductile remains largely unresolved. A recent study by Befus et al. (2014) estimated the decompression rate at Douglas Knob, in the Yellowstone volcanic field, at between 8×10^{-6} and 3×10^{-5} MPa/s, based on the analysis of microlites. Although the authors did not focus on the outgassing mechanisms, microlites in obsidian may preserve useful information about both magma ascent and outgassing mechanisms, and are worth analyzing. Because obsidian is glassy and included microlites are very small (typically smaller than several tens of microns), microlites have traditionally been very difficult to analyze.

Numerical studies have shown a relationship between microlite textures and magma ascent dynamics (Toramaru, 1991, 2008), and experimental studies also provide quantitative data on the kinetics of nucleation and growth processes due to decompression-induced crystallization (e.g., Hammer and Rutherford, 2002; Couch et al., 2003; Martel and Schmidt, 2003; Shea and Hammer, 2013). In this paper, we utilize the textures and compositions of microlites in highly viscous rhyolitic obsidian lava in order to ascertain the causes of outgassing.

We performed chemical and textural analyses of Tokachi–Ishizawa (TI) obsidian lava from Shirataki, northern Hokkaido, in Japan, where the structure of the lava can be observed from the outer obsidian region to the inner rhyolite region. Therefore, the TI lava provides an opportunity to investigate the correlation between structure and microtextures in a single flow. First, we describe the structure and texture of TI lava, and present the results of chemical and textural analyses on the lava. Second, we estimate the water exsolution rates during magma ascent in the volcanic conduit by examining the equilibrium pressure, temperature, and water concentration using the Rhyolite-MELTS program and using a microlite number density (MND) decompression rate meter. Third, by combining these estimated pressures, temperatures, water concentrations, and decompression rates with a simple mechanical model, we suggest that the development of ductile permeability, rather than brittle fracturing, was the dominant process controlling outgassing.

2. Geological setting and lava structure

In Shirataki, Hokkaido, in northern Japan, dacite and rhyolite magma erupted during the late Pliocene and formed a pyroclastic deposit. This magmatism formed a caldera structure, which corresponds with a Bouguer gravity anomaly (Yamamoto, 2004) and is called the Horoka–Yubetsu caldera (Fig. 1).

After formation of the Horoka–Yubetsu caldera, eruption of aphyric rhyolite magma started, and explosive eruptions within the caldera formed several pyroclastic deposits, including obsidian fragments as lake deposits (Horoka–Yubetsu Formation; Konoya et al., 1964). Subsequently, effusive aphyric rhyolite lava flowed down into the caldera lake where it was autobrecciated. Pyroclastic materials buried the caldera lake, and after that volcanic activity was subaerial.

At the caldera rim and inside, aphyric rhyolite lava that erupted at ca. 2.2 Ma comprises 10 flow units (Fig. 1; Wada and Sano, 2011) that can be classified into four geochemical groups based on glass compositions, especially on a diagram of FeO* vs. CaO (Fig. 2). The chemical compositions of the Tokachi–Ishizawa (TI) lava belong to the Tokachi–Ishizawa-B series and show little chemical variation. In the TI lava, we can observe the internal structure of a single flow unit, as illustrated below.

The typical structure of obsidian lava is thought to consist of an outer obsidian region and an interior rhyolite region (Cas and Wright, 1987; Manley and Fink, 1987; Swanson et al., 1989; Stevenson et al., 1994). Within the TI lava, the internal structures of single obsidian–rhyolite lava, except for the upper obsidian region, are exposed. An exposure about 50 m high and 100 m wide can be observed, although the lava is partially covered with vegetation (Fig. 3a). A cross-section of the TI lava shows the following sequence from the bottom up: an obsidian region (Ob), a boundary banded region (BB) of obsidian and rhyolite (BB-obs and BB-rhy), and a rhyolite region (Rhy; Fig. 3a). The upper rhyolite region has probably been lost to weathering and erosion. In this paper, we define rhyolite and obsidian as follows: rhyolite has perlitic cracks in the glass and contains some crystalline material, namely spherulites and lithophysae, whereas obsidian includes no such material at all. The TI lava is underlain by autobrecciated aphyric lava and a lake deposit comprising pyroclastic material.

The Ob consists of single compact obsidian about 7 m high. The overlying BB unit consists of thin obsidian (<10 mm in width) and rhyolite bands (Fig. 3b). In BB, the fraction of obsidian bands decreases toward the interior of the lava. The rhyolite region consists of rhyolite bands with variable vesicularity, crystallinity, and thickness (Fig. 3c, d). Bands including spherulites and lithophysae are <20 mm thick. Vesicles are <30 mm in diameter (Fig. 3d).

Open squares in Fig. 3a indicate sampling points in the obsidian region (samples Ob-1 and Ob-2), the boundary banded region (sample BB), and the rhyolite region (samples Rhy-1 and Rhy-2). In the boundary banded region, we collected samples from both obsidian (BB-obs) and rhyolite (BB-rhy). The Rhy-1 sample is from the lowermost part of the rhyolite region, about 2 m above the BB, whereas the Rhy-2 sample is from the interior part of the rhyolite region about 10 m above the BB (Fig. 3a).

3. Rock textures

The analyzed obsidian is aphyric, mostly composed of glass (>97%), and contains microphenocrysts of magnetite (0.05–0.1 mm), microlites of plagioclase (<0.2 mm), K-feldspar (<0.05 mm), oxides (<0.05 mm) (Fig. 4), and rare biotite (<0.01 mm). Plagioclase phenocrysts (0.4–1.0 mm) are rare. Plagioclase microlites comprise about 2% by volume of the obsidian, as estimated by measuring their total area in backscattered scanning electron microscope (SEM) images. The paragenesis of plagioclase and K-feldspar, which is used for an estimate of