Magma fracturing and friction: Implications for volcanic eruptions

A volcanic eruption is a dynamic phenomenon that releases magma from Earth's interior to the surface. Magma is molten rock, which ascends as a viscous fluid in a volcanic conduit that connects the magma reservoir to the surface. A central issue in volcanology is to understand how magma ascends in the conduit because the process of magma ascent is thought to control the explosivity and variety of eruption style. For instance, magma vesiculates during magma ascent and subsequent decompression because it contains volatiles such as water and carbon dioxide. This vesiculation strongly reduces magma density, which becomes a driving force of magma ascent and eruption.

In the last two decades, volcanologists have discovered an important process that may have a large impact on magma ascent dynamics: "magma fracturing and friction" [1]. Magma is viscous fluid, but it has viscoelasticity and shows brittle deformation under high shear flow. If magma shows the transition between viscous and brittle deformation during ascent, the magma ascent dynamics are affected, which may explain the observations at the surface that have been a mystery for many years, such as the cause of volcanic seismicity [2]. Recently, magma fracturing under high temperature and pressure conditions was directly observed using synchrotron radiation X-ray radiography and computed tomography [3]. The direct observation showed that magma fracturing is a common process for silicic magma, and the fracturing results in shear localization. A fractured and shear-localized zone becomes a magmatic fault, and the deformation mode changes from viscous flow to friction. This transition also changes the explosivity of magma ascending in the conduit because viscous deformation causes bubble coalescence and enhances outgassing [3]. To investigate the transition between viscous flow and frictional sliding, we performed friction tests for magmatic gouge at high temperatures [4].

The friction tests were performed using a rotational deformation apparatus set on an X-ray imaging beamline **BL20B2**. The magmatic gouge zone was simulated by sandwiching rhyolitic glass powder with rhyolitic glass discs (Fig. 1). The sample was set in a graphite cylinder and heated to temperatures of 800 and 900°C in the furnace. Normal stresses on the discs were controlled to be 1–10 MPa, and a disc was rotated at rates of 0.1 to 10 rpm. Sample deformation at high temperature was observed using X-ray radiography (Fig. 1). We were able to directly observe the sample using this experimental system because the furnace has a small hole for the X-ray path, hence only the graphite and sample are on the path.

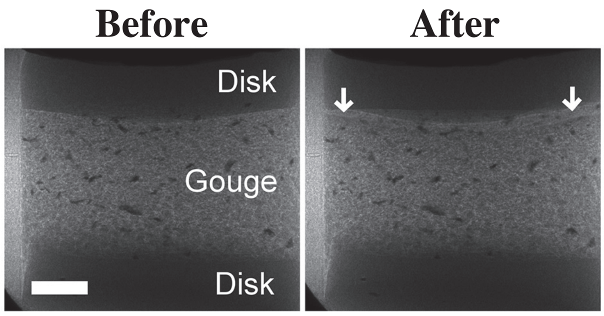

Fig. 1. *In situ* X-ray radiographic image of deforming samples. The images were taken just before and after the deformation at 800°C under a normal stress of 1 MPa. Gray and light-gray parts are disk and granular melts (gouge), respectively. In this experiment, frictional sliding was observed, and a sharp fault in the fractured zone (indicated by white arrows in After) was also found. Small iron particles (black particles), used as a strain maker, are found in granular melts. The white bar indicates a 1 mm scale.

We identified the flow type based on X-ray radiography and the relationship between the rotational rate and torque necessary to twist the sample. For viscous flow, the torque is proportional to the rotational rate, while the torque is almost constant under the rotational rate used in this study when frictional sliding is dominant. We observed both viscous flow and frictional sliding depending on temperature, normal stress, and rotational rate. At a temperature of 800°C, the magmatic fault showed frictional sliding along the boundary between the granular melt and the upper disk at normal stresses of 1 and 5 MPa. On the other hand, viscous deformation without a clear localization and frictional sliding dominated at a temperature of 900°C under normal stresses of 5 and 10 MPa and rotation rates of 0.1 to 1 rpm. The flow regime was well determined by using the ratio of viscous shear stress to normal stress ($T = \eta\dot{\gamma}/\sigma$, where η, $\dot{\gamma}$, and σ represent melt viscosity, shear strain rate, and normal stress, respectively) (Fig. 2(a)). The boundary between viscous flow and frictional sliding is 0.45–0.79. This result also indicates that the friction coefficient of magmatic faults is 0.45–0.79.

To investigate the flow regime (viscous flow vs. frictional sliding) during magma ascent, we calculated the T value of magmatic faults and compare it with the regime map (Fig. 2(b)). The T value increases with magma ascent because normal stress decreases and magma viscosity increases because of melt dehydration. The rate of magma deformation during its ascent is a parameter that is not well constrained. The strain rate yielding in magma can be directly observed from the shapes of the bubbles in pyroclasts and lava, which is on the order of ~10^{-2} and 10^{-7} s^{-1}, respectively [5]. On the other hand, numerical simulation of magma flow dynamics in the conduit shows a strain rate of 1 s^{-1} for explosive eruption and lava effusion rates provide a bulk deformation rate of $10^{-3.5}$ s^{-1} (see the details in [4]). Here, we simply assume a rate of 1 and 10^{-3} s^{-1} to discuss the cases of explosive and effusive eruption, respectively. When we assume strain rate yielding in magma to be 1 s^{-1}, magma shows frictional sliding at depths shallower than 200–600 m. This means that flow type changes from viscous flow to frictional sliding at depth, and the transition can reduce apparent magma viscosity. This may cause rapid ascent of the magma column along a magmatic fault and finally explosive volcanism (Fig. 3). In contrast, when the strain rate is 10^{-3} s^{-1}, magma shows frictional sliding only at very shallow depths (<~50 m). This means that magma experiences viscous deformation, which enhances magma outgassing (Fig. 3) [3]. In this case, the potential for magma explosion is reduced and lava effusion is expected, and the lava plug would show friction only near at the surface, as observed at Mt. Unzen in Japan and Mt. St. Helens in the U.S.A. As shown here, the coupled effect of magma rheology, i.e., the transition between viscous flow and frictional sliding, and magma outgassing, may be a controlling factor of magma ascent rate and eruption style.

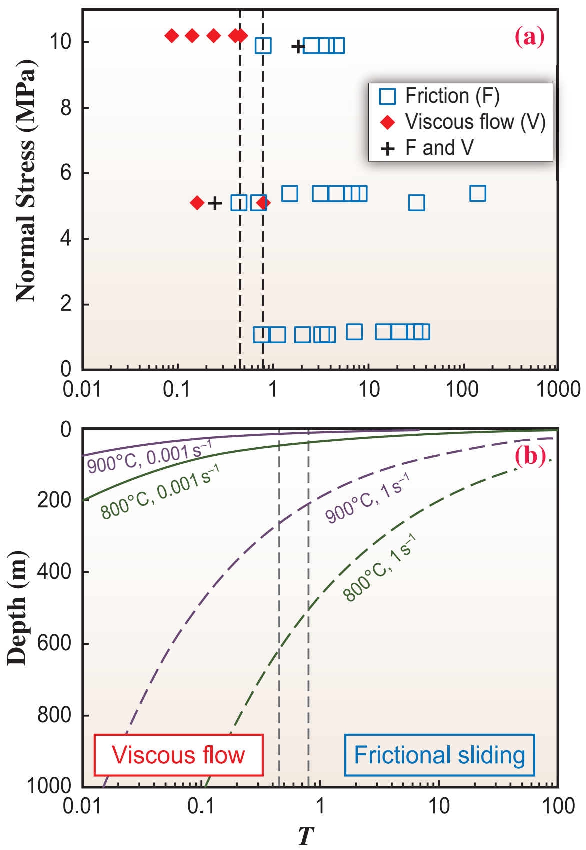

Fig. 2. **(a)** Flow type represented in the T-normal stress diagram. Blue squares and red diamonds represent frictional sliding (friction, F) and viscous flow (V), respectively. Crosses represent the transition from viscous flow to frictional sliding during a constant rotation rate. Two vertical dashed lines (T = 0.45 and 0.79) represent the transition zone between viscous flow and frictional sliding. **(b)** Evolution of the T value during the ascent of silicic magmas at 800 and 900°C. [4]

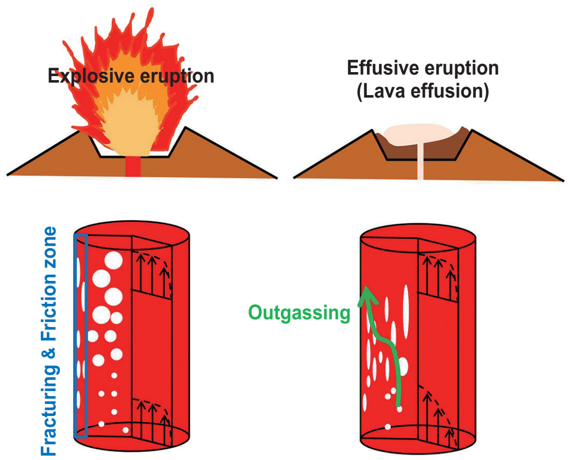

Fig. 3. Schematic model of magma ascent during explosive (left panel) and effusive (right panel) eruptions. During explosive eruption, magma experiences shear localization and results in the formation of a fractured and friction zone along the conduit. Magma can ascend rapidly along this zone. During effusive eruption, magma shows viscous flow, and the outgassing is enhanced by viscous deformation. Only at very shallow parts in the conduit, magma ascent is dominated by friction, resulting in lava effusion.

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References

[1] D.B. Dingwell: Science **273** (1996) 1054.
[2] H. Tuffen *et al.*: Nature **453** (2008) 511.
[3] S. Okumura *et al.*: Earth Planet. Sci. Lett. **362** (2013) 163.
[4] *S. Okumura, K. Uesugi, M. Nakamura, O. Sasaki: J. Geophys. Res.* ***120*** *(2015) 2974.*
[5] A. Rust *et al.*: J. Volcanol. Geotherm. Res. **122** (2003) 111.