



# Rheological properties of dome lavas: Case study of Unzen volcano

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## ABSTRACT

Transitions between effusive and explosive styles of lava dome eruptions are likely accompanied by changes in lava rheology. The common presence of crystals in dome lavas produces a complex non-Newtonian rheology. Thus models of such complex rheology are essential for volcanic eruption models. Here, we have measured the rheology of natural Unzen lavas with a compressive uniaxial press operating at stresses between 1 and 70 MPa and temperatures between 940 and 1010 °C. Crystal-rich Unzen lavas are characterised by two essential rheological features which produce non-Newtonian effects. The first is an instantaneous response of the apparent viscosity to applied stress which requires that the magma be described as a visco-elastic fluid that exhibits shear-thinning. The second effect takes the form of a time-dependence of the viscosity at moderate to high stress ( $\geq 10$  MPa). In this regime, the apparent viscosity slowly decreases as increasing fracturing of the phenocrysts and the groundmass occurs. Fragmentation of crystals and alignment of crystal fragments are observed to produce flow banding-effects which in turn lower the apparent viscosity of natural dome lavas. Ultimately, deformation may lead to complete rupture of the lava if the stress is sufficient. Cracking thus stands as an important process in natural dome lava rheology. The ubiquitous non-Newtonian rheology of dome lavas, observed experimentally here, needs to be adequately treated in order to generate appropriate eruption models.

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## 1. Introduction

Unzen is a back-arc volcano enclosed in the Beppu–Shimabara graben, located on Shimabara peninsula in Kyushu Island, Japan. The most recent activity of Unzen began in November 1990 after 198 years of quiescence. An initial phreato-magmatic eruption was later followed by an explosion in April 1991 and the first lava dome extrusion in May 1991. Over the following 5 years many cycles of dome growth and collapse occurred as Unzen underwent several transitions in eruptive intensity and style (Nakada and Motomura, 1999). Activity ranged from vulcanian explosions to phreato-magmatic eruptions and lava dome extrusions, which culminated in the generation of pyroclastic and debris flows (Nakada and Motomura, 1999; Nakada et al., 1999; Fujii and Nakada, 1999). Ultimately, thirteen different domes were created, most destroyed by exogenous or endogenous growth, and activity ending in February 1995. Understanding what drives transitions in eruptive style is critical to volcanic hazard assessment. During the eruptive activity of Unzen two overlaying patterns of activity were apparent: 1) a long-period cycle characterised by two phases 20 months in length, and 2) a short-term cycle in which the eruptive

regime alternated between exogenous and endogenous dome growth. The long-period cycles have been attributed to the country rock rheology (Maeda, 2000). According to that study the long-period cycles could find their explanation in the elastic properties of the rocks surrounding the volcanic conduit via changes in the volcanic conduit dimension. This idea has been supported by Noguchi and co-authors who developed it in terms of an effusion rate efficiency linked to the crystal content and characteristics (i.e. length, crystal fraction and microlite number density) (Noguchi et al., 2007, 2008). The shorter period cycles have to date been explained by two theories: the self-sealing model (Nakada and Motomura, 1999) and the rupture model (Goto, 1999). Awareness is increasing that eruptive style transitions may well be driven by the complex rheology of crystal- and bubble-bearing lavas (D'Oriano et al., 2005). Thus, a better understanding of the lava rheology involved at Unzen (e.g. how it flows and/or fails) is essential to constrain both the self-sealing and rupture models.

Suspensions and highly crystalline lavas have complex rheologies, and their definition is also technically difficult. The addition of rigid particles in a melt increases its relative viscosity (ratio between the effective viscosity and the viscosity of the solvent). At low crystal fraction, suspensions behave as Newtonian fluids (i.e., the stress to strain-rate relationship is linear and passes through the origin) and their relative viscosity can be approximated by empirical models such as the Einstein–Roscoe equation (Roscoe, 1952). With increasing crystal fraction, the relative viscosity increase follows a power law (Eilers,

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1941; Ward and Whitmore, 1950a,b; Roscoe, 1952; Vand, 1948; Gay et al., 1969; Chong et al., 1971; Gadalamaria and Acrivos, 1980; Ryerson et al., 1988; Woutersen and Kruijff, 1991; Jones et al., 1991, 1992; Lejeune and Richet, 1995). Numerous attempts have been made to improve this law but none have achieved widespread application (Mooney, 1951; Bagnold, 1954; Krieger and Dougherty, 1959; Thomas, 1965; Gay et al., 1969; Batchelor and Green, 1972; Jeffrey and Acrivos, 1976; Batchelor, 1977). Moreover, at high crystal content, the crystal network effectively hampers viscous flow once a critical melt fraction is reached and the rheology becomes strain-rate dependent, i.e. non-Newtonian (Lejeune and Richet, 1995; Bruckner and Deubener, 1997; Deubener and Bruckner, 1997; Lavallee et al., 2007; Caricchi et al., 2007; Champallier et al., 2008). The mechanical heterogeneities generated by the presence of crystals in a melt allow stress localisation and favour the formation of shear bands causing the premature generation of cracks. The apparent viscosity is then no more homogeneous. It cannot be seen as an effective viscosity in the sense of a phase mixture in continuum but apparent in the sense of acute strain localisation and material failure. This apparent viscosity can be seen as a macroscopic viscous flow that may exhibit discontinuous brittle behaviour on a local scale. It commonly bridges viscous-flow to dislocation-creep behaviour. This has been observed for some time in the structural geology of crystalline rocks (Nicolas et al., 1977; Poirier et al., 1979; Poirier, 1980, 1985), polycrystalline flow (Vandermolen and Paterson, 1979; Nicolas, 1984; Shea and Kronenberg, 1992; Lejeune and Richet, 1995; Rutter and Neumann, 1995; Lavallee et al., 2007), metallurgy (Jonas et al., 1976; Canova et al., 1980) and even in polymers (Bowden and Jukes, 1969; Bowden, 1970). As a result, measurements of the apparent viscosity of a suspension cannot yet be adequately described. Differentiating each effect of the apparent viscosity decrease is needed in order to create an appropriate model. Here, we study the stress/strain-rate dependence of Unzen lava rheology. In particular we describe the transition from viscous flow to brittle behaviour. Providing evidence that this description is capable of explaining the recurring critical rupture of lava domes during the recent activity of Unzen.

## 2. Methods

We employed a parallel plate geometry generated via a uniaxial press to study the viscosity of natural dome lavas subject to different applied stresses (1–70 MPa) and temperatures (940–1010 °C) (Hess et al., 2007a). The apparatus is useful for volcanological studies because it can accommodate large samples (up to 100 mm in length and diameter) and it uses conditions equivalent to those found in deforming lava domes. We used large cylindrical samples (80 mm high by 40 mm in diameter) in order to overcome scaling issues arising from the large size of phenocrysts in Unzen lavas. Samples with an aspect ratio of 2 were chosen in order to meet the classic standards of parallel plate rheometry (Hawkes and Mellor, 1970). We inserted three equidistant thermocouples inside the long axis of the sample to continuously monitor the evolution of temperature. The samples were placed between the pistons of the press and heated for 7 h. The upper piston was then lowered until contact with the upper part of the sample was made and this position was maintained for 1 h in order to reach perfect thermal equilibrium between piston and sample. Various loads were then applied and the load and displacement were recorded at a rate of 10 measurements per second. The apparent viscosity was calculated from the measured rate of change of the sample's length using Gent's equation (Gent, 1960; Hess et al., 2007a):

$$\eta_a = \frac{2\pi Fh^5}{3V \left( \frac{dh}{dt} 2\pi h^3 + V \right)} \quad (1)$$

Where  $\eta_a$  is the apparent viscosity,  $F$  is the force,  $h$  the length between the two pistons and  $V$  the volume of the sample.

**Table 1**

Chemical composition of Unzen glass determined by electron microprobe (left), and from Nakada et al. (right; 1999)

	This study-Weight% (average of 11 measurements)	Mean deviation	Nakada-Weight% (average of 7 measurements)	Mean deviation
SiO <sub>2</sub>	78.34	0.23	77.60	1.41
TiO <sub>2</sub>	0.43	0.03	0.32	0.07
Al <sub>2</sub> O <sub>3</sub>	11.88	0.18	11.21	0.43
FeO*	0.84	0.09	0.94	0.20
MnO	0.03	0.02	0.04	0.03
MgO	0.09	0.01	0.11	0.07
CaO	0.49	0.17	0.63	0.21
Na <sub>2</sub> O	3.06	0.08	2.95	0.19
K <sub>2</sub> O	4.79	0.13	4.70	0.37
P <sub>2</sub> O <sub>5</sub>	0.02	0.02	X	x
Total	99.97	0.11	98.50	0.96
Agl	0.86	0.02	0.88	0.04

FeO\* is the total iron measured. The Agpaitic index (i.e.  $Agl = \frac{Na_2O + K_2O}{Al_2O_3}$ ) indicates a minor viscosity dependence on the chemical composition variations.

As the viscosity of silicate melts is strongly dependent on their chemical composition. Hence, we determined the chemical composition of the interstitial melt in order to understand the apparent viscosity increase caused by the presence of crystals. The chemistry was determined with a CAMECA SX50 electron microprobe. A careful calibration of the instrument was done before each measurement and special care was taken to minimise sodium loss. We used a current of 5 nA, a voltage of 20 kV and a 20-micron diameter beam. The eruptive products of Unzen are andesitic and part of the calc-alkaline series. The interstitial glass phase, however, is rhyolitic (Nakada and Motomura, 1999). Here we studied lava dome samples from 2000 and 2001 fieldwork conducted on different block-and-ash flows deposit. In this study we used samples with low open porosity; namely Muz2000A, Muz2001A and Muz2001B with an open porosity of 3.87, 6.74 and 5.7%, respectively. We also emphasise that the glass matrix has an Agpaitic index below one (see Table 1). Chemical variations have consequently a small effect on the viscosity (Dingwell et al., 1998; Hess et al., 2001). Our work is in agreement with previous rheological studies of Unzen's interstitial melt phase (e.g. Nakada and Motomura, 1999; Goto, 1999). The recent eruptive products of Unzen volcano are andesitic containing 0.1 wt.% to 0.2 wt.% volatiles for the dome (lobe 1–13) and 0.1 wt.% for the spine (final stage of the eruption) (Nakada and Motomura, 1999; Kusakabe et al., 1999; Noguchi et al., 2007, 2008). The lava erupted at around 780–880 °C (Nakada et al., 1999; Holtz et al., 2005) and originated from the mixing of a hot, aphyric, dioritic magma with a cold, crystallised, granitic magma. Petrographic analyses suggest that the phenocrysts originally from the granitic magma were entrained by the ascending dioritic magma. The phenocrysts total fraction, approximately 30 vol.%, is mainly composed of plagioclase or hornblende, with a lesser amounts of quartz, biotite and magnetite. Phenocrysts are often clustered (Nakada and Motomura, 1999 and Fig. 1-A). Plagioclase phenocrysts were often partially fractured (Fig. 1-B). The groundmass is partially crystallised with 40+/- 10 vol.% of microlites of plagioclase and some pyroxenes and biotite. An important fraction of the microlites appears to be fragments of broken phenocrysts, possibly produced during ascent in the conduit. We estimated the crystal and vesicle fractions of the samples by automated optical counting. This technique can be reliably used to characterise Unzen samples because the crystal assemblage is simple and distinct. Our method is based on colour coding of scanned images. The ratios between red, green and blue colours help distinguish between crystal types. The fingerprint of each crystal can thus be used to determine and patch the surfaces of all the crystals of that type. Each patch is then numbered and oriented, and thus the number of crystals, their surface fraction and the anisotropy can be estimated. This technique resolved estimates of 18.16 vol.% of plagioclase crystals and

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