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Influence of melt viscosity of basaltic and andesitic composition on seismic attenuation in partially molten gabbronorite

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ABSTRACT

The characteristic frequencies at which two different melt-related attenuation mechanisms occur in partially molten gabbronorite are computed as a function of aspect ratios of the melt-filled cracks, and the melt viscosity. The computations were done for basaltic and andesitic melts. The melt viscosity is constrained by (i) laboratory measurements performed in the range 10^8–10^{14} Pa s with a creep apparatus and in the range 10^{-1} to 10^5 Pa s with a rotational Couette viscometer, and (ii) modeling of viscosity at high temperatures. The results of the characteristic frequency calculations suggest that melt squirt flow is a viable attenuation mechanism at seismic frequencies for aspect ratio of melt inclusions in the range 10^{-3} to 10^{-2} for the andesite, and 10^{-4} to 10^{-3} for the two basalts.

1. Introduction

Eruption dynamics are controlled by magma viscosity. The flow velocity of lava flows depends on magma viscosity and density. Because melt flow is primarily determined by viscosity, viscosity measurements of basaltic and andesitic melts are also important to interpret seismic attenuation tomography models in partially molten mafic systems, for instance P-wave attenuation structure of the fast-spreading East Pacific Rise (Wilcock et al., 1995). Viscosity data are rare for basaltic melts (e.g., Shaw, 1969; Murase and McBirney, 1973; Ryan and Blevins, 1987; Giordano and Dingwell, 2003), and particularly for basalts with FeO content in the range 8–11% or for basalts with high-MgO content (~14% MgO). Measurements of viscosity of picritic basalt (high-MgO content) are important to constrain the rheology of lavas coming from active volcanoes. Picritic basalt flows were observed at various active volcanoes: Piton de la Fournaise (Albarède et al., 1997), Hawaii (Dzurisin et al., 1995) and Pitcairn (Hekinian et al., 2003). The melt phase distribution and melt flow mechanisms are difficult to determine using seismic observations of Q^{-1} (i.e., attenuation coefficient of the seismic energy), in particular because of high-temperature gradient(s) in the attenuating zone. Melt viscosity is very sensitive to temperature. Viscosity also depends on the chemical composition of the melt phase and the chemical composition changes during crystallization processes (e.g., Marsh, 2006). Combined results from Richet et al. (1996), Liebske et al. (2003) and Vetere et al. (2006) suggest that viscosities of anhydrous andesitic melts are independent of pressure.

A viscosity increase should lower the main frequency peak of the related attenuation mechanism (squirt flow and/or viscous flow) (e.g., O'Connell and Budiansky, 1977).

The main goal of this paper is to address the effect of melt viscosity on the attenuation peak due to melt flow in partially molten gabbronorite in the seismic frequency range (Fontaine et al., 2005). We quantified the change of viscosity of the melt phase with temperature for basaltic and andesitic compositions with 8–11% FeO and 4–15% MgO (in weight percent of oxides). The compositions of two analyzed melt phases (picritic basalt 1 and andesitic melt) are similar to average compositions of glasses and dendrites present after torsion oscillatory deformation experiments at high temperature (1441 K) and low frequencies (2×10^{-3} to 2×10^{1} Hz) on fine-grained gabbronorite samples (Fontaine et al., 2005). The average composition of glasses is similar to the andesitic composition of the present study, while the composition of picritic basalt 1 melt is similar to the average dendrite compositions. In the first part, we present new viscosity measurements on an andesite melt from the glass transition to superliquidus temperatures, and measurements at low temperature realized on two picritic basalts. The

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Table 1
Chemical compositions of the measured samples (in weight of oxides, %)

	SiO_2	Al_2O_3	FeO	CaO	MgO	Na_2O	TiO_2	K_2O	Density
Synthetized andesite	55.76	18.23	9.16	10.52	4.18	1.74	0.27	0.14	2.68
Synthetized picritic basalt 1	48.53	10.57	8.86	17.62	13.77	0.36	0.23	0.06	2.90
Synthetized picritic basalt 2	44.31	11.06	11.11	18.07	14.84	0.36	0.21	0.04	2.97

Measurements analyzed on a Cameca SX100 electronic microprobe (beam parameters 20 kV and 10 nA).

viscosity is computed for two picritic basalts at high temperature using the model of Bottinga and Weill (1972). In the second part, we relate our viscosity results to seismic attenuation through the characteristic frequency of two attenuation mechanisms caused by melt flow: melt squirt flow and viscous flow.

2. Experimental methods and experimental results on viscosity

2.1. Samples

The compositions and densities of the measured melts are listed in Table 1, along with the densities of all glasses measured with the Archimedes method, toluene being used as immersion liquid. Starting glass was first prepared from dried, reagent grade MgO, SiO_2, $CaCO_3$, Na_2CO_3 and Fe_2O_3 as described by Schairer and Yagi (1952). The slowly decarbonated mixture was melted at 1923 K in air in a platinum crucible previously used for preparing iron-bearing melts, reground and remelted three times to ensure chemical homogeneity. The obtained glass was quenched in air on a copper plate. Electron microscopy observations showed that the samples were homogeneous and devoid of crystallization products. Oxidation state of the iron in the glasses did not change during the viscosity measurements (e.g., Magnien et al., 2004).

2.2. Creep apparatus

A creep apparatus built by Neuville and Richet (1991) was used to measure under uniaxial compression the viscosity of silicate melts in the range 10^8–10^{14} Pa s at temperatures between 773 and 1323 K. The strain rate in a sample of length l is measured as a function of an applied constant stress σ at a fixed temperature. The ratio of stress to strain rate in pure shear yields the viscosity directly. Temperature differences along the cylindric samples were lower than 0.2 K.

2.3. Rotational Couette viscometer

The experimental device used in this study was built by Neuville (1992, 2006) and uses the concentric cylinder method of Couette to measure the viscosity of silicate liquids in the range 10^{-1} to 10^5 Pa s at temperatures between 1273 and 2023 K. The fluid is assumed to be Newtonian. The viscosity is determined from measurements of the torque by a commercial apparatus, Rheomat 115, using a rotational velocity between 0.05 and 780 rpm. A calibration with a U.S. National Bureau of Standards (NBS) glass is required (Neuville, 2006). Temperature gradients inside the crucible that contains the melt sample are less than 2 K for 5 cm vertically and 1 K for 2.7 cm radially at 1773 K, and slightly less at 2073 K. The viscosity of the andesitic melt was determined using the Couette viscometer.

2.4. Experimental results on viscosity

The reported viscosities are the average of 15 or more measurements at different stresses, which generally differ by less than 0.03 log units. Our viscosity measurements on two picritic basalts and one andesite are plotted in Fig. 1 as a function of reciprocal temperature. Viscosity variations of andesitic melt as a function of temperature are not linear from high to low temperature (Fig. 1(A)). We did not undertake high-temperature measurements of basaltic melts.

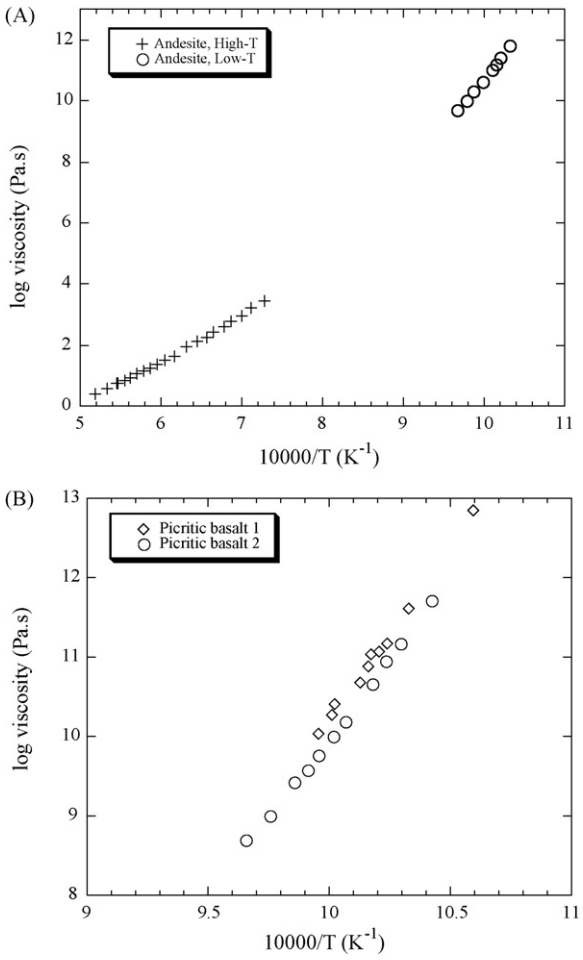

Fig. 1. The new experimental dataset is plotted for the three studied melts. (A) Low- and high-temperature measured values of viscosity for the andesitic melt as a function of reciprocal temperature. (B) Low-temperature viscosity data of basaltic melts as a function of reciprocal temperature.

3. Discussion

3.1. Comparison of viscosity measurements with previous experimental studies

Our measurements are compared in Figs. 2 and 3 to experimental data (Shaw, 1969; Murase and McBirney, 1973; Ryan and Blevins, 1987; Neuville et al., 1993; Richet et al., 1996; Giordano and Dingwell, 2003). Our measured andesitic melt viscosities are close to those measured by Neuville et al. (1993) at low tempera-