Propagation of P and S-waves in magmas with different crystal contents: Insights into the crystallinity of magmatic reservoirs

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ABSTRACT

Increasing amount of crystals tends to reduce the mobility of magmas and modifies its elastic characteristics (e.g. [Caricchi, L. et al., 2007. Non-Newtonian rheology of crystal-bearing magmas and implications for magma ascent dynamics. Earth and Planetary Science Letters, 264: 402–419.; Bagdassarov, N., Dingwell, D.B. and Webb, S.L., 1994. Viscoelasticity of crystal- and bubble-bearing rhyolite melts. Physics of the Earth and Planetary Interior, 83: 83–99.]). To quantify the effect of crystals on the elastic properties of magmas the propagation speed of shear and compressional waves have been measured at pressure and temperatures relevant for natural magmatic reservoirs. The measurements have been performed in aggregates at variable particle fractions (ϕ=0–0.7). The measurements were carried out at 200 MPa confining pressure and temperatures between 300 K and 1273 K (i.e. across the glass transition temperature (Tg) from glass to melt). The specimens were mixtures of a haplogranitic melt containing 5.25 wt.% H_2O and variable amounts of sub-spherical alumina particles. Additional experiments were carried out on a sample containing both, crystals and air bubbles. The temperature derivatives of the shear (dVs/dT) and compressional wave (dVp/dT) velocities for pure glass and samples with a crystal fraction of 0.5 are different below and above the glass transition temperature. For a crystal fraction 0.7, only dVp/dT changed above the Tg. In the presence of gas bubbles, Vp and Vs decrease constantly with increasing temperature. The bubble-bearing material yields a lower bulk modulus relative to its shear modulus. The propagation velocities of compressional and shear waves increase non-linearly with increasing crystal fraction with a prominent raise in the range $0.5<\phi<0.7$. The speed variations are only marginally related to the density increase due to the presence of crystals, but are dominantly related to the achievement of a continuous crystal framework. The experimental data set presented here can be utilized to estimate the relative proportions of crystals and melt present in a magmatic reservoir, which, in turn, is one of the fundamental parameters determining the mobility of magma and, consequently, exerting a prime control on the likelihood of an eruption from a sub-surficial magma reservoir.

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1. Introduction

In the making of an eruption, the ascent of magma from a reservoir is strongly controlled by the viscosity of the magma which is in turn strongly influenced by its crystal fraction (Lejeune and Richet, 1995; Sparks et al., 2000; Caricchi et al., 2007; Costa et al., 2007; Lavallée et al., 2007). For this reason, the quantification of the crystallinity of magmatic reservoirs below active volcanoes is a fundamental prerequisite for successful volcanic risk assessment. The inversion of seismic data is the prime tool to obtain information on the physical state of magma reservoirs (e.g. Singh et al., 1998). Systematic experimental investigation of shear (Vs) and compressional wave velocities (Vp) in magmatic suspensions containing different crystal fractions has not been conducted. Several studies have focused on the characterization of the elastic moduli and Vp and Vs in silicate glasses and melts of different compositions (e.g. Webb and Dingwell, 1990;

Askarpour et al., 1993; Bagdassarov et al., 1993; Webb and Courtial, 1996; Schilling et al., 2003; Faul et al., 2004; Jackson et al., 2004; Scheu et al., 2006). Forced torsion experiments have been performed to determine shear moduli and attenuation variations as a function of crystal fractions and a limited number of experiments were conducted on crystal–bubble–melt suspensions (Bagdassarov et al., 1994; Bagdassarov, 1999; Müller et al., 2003). These experimental data combined with theoretical models (Mavko, 1980; Schmeling, 1985; Taylor and Singh, 2002) have demonstrated that the microstructures and, in particular, the distribution of melt relative to minerals, play a fundamental role in determining the elastic properties of a melt-bearing material. In this study, suspensions of particles and melt containing 5.25 wt.% water were synthesized to represent four states that may characterize the microstructure of magma: a fully molten state, a suspension of crystals in a melt phase (50 vol.% crystals), a crystal supported mush (70% crystal), and a bubbly crystal mush (74% crystal and 18% bubbles). P and S-wave determination for these four suspensions were carried out at a pressure of 200 MPa and temperatures from room to 1273 K, which is within the range of conditions inferred to be typical for magmatic reservoirs present below active

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volcanoes (e.g. Bachmann and Dungan, 2002; Rutherford and Devine, 2003). The measurements were performed with the pulse transmission technique applying a frequency of 3 MHz. The dependency of the measured elastic moduli and, consequently, Vp and Vs on frequency is considered and taken into account in the discussion of the data.

2. Preparation and characterization of synthetic samples

Weighted aliquots of powdered oxides and hydroxides were thoroughly mixed to obtain a fine-grained mixture of haplogranitic composition containing 5.25 wt.% H_2O; the nominal composition is given in Table 1. Powders were pressed into stainless steel, can-shaped canisters and separated from steel by chemically less reactive molybdenum foils. The containers were welded shut; during welding they were cooled to prevent water escape from the starting material by immersing them for almost their entire length in water. After welding, the tightness of the closure was checked under water in vacuum condition. To synthesize the glass, the containers were hot isostatically pressed (HIP) at 180 MPa and 1373 K for 24 h in a large volume internally-heated pressure vessel. The resulting product was a chemically homogeneous glass that was free of microlites visible in back scattered mode in an electron microprobe (Table 1). The H_2O content of the starting glass after synthesis in the large volume internally-heated pressure vessel was measured by Karl-Fisher titration, Fourier-Transform Infrared spectroscopy and micro-Raman spectroscopy and was found to be in agreement with the nominal value of 5.25 wt.% within analytical uncertainty (Ardia et al., in press). H_2O contents were not determined after physical property measurements, but there is no reason to suppose that H_2O was lost during the measurements at the experimental conditions employed. In fact the water saturation for the haplogranitic composition used at the experimental pressure (200 MPa) and at the maximum experimental temperature (1273 K; 6.1 wt.%; Moore et al., 1998) is well above the amount of water dissolved in the starting material (5.25 wt.%).

A cylinder of 20 mm length and 15 mm diameter was drilled from the glass to perform elastic property measurements on the crystal free melt. The remaining glass was subsequently powdered to a grain size of about 5 µm using an agate mortar and a sphere mill. Samples containing 50, 70 and 90 vol.% crystals were prepared by mixing the powdered glass with corundum particles (supplier: Friatec AG, D-68229 Mannheim, Germany) having a grain size of about 150 µm. The relative volumetric proportions of corundum and glass were calculated using density data for polycrystalline alumina aggregates as given by Chung and Simmons (1968) and for the hydrous glass using the models of Lange (1994) and Och and Lange (1997). The mixtures of glass and particles were hot isostatically pressed at 200 MPa and 1023 K for 1 h producing samples of 40–45 mm length and 22 mm diameter. Cylindrical specimens of 35–40 mm length and 15 mm diameter were drilled from the hot pressed material and double polished to obtain parallel faces. The density (ρ) of the specimens was measured prior and after the experiments by weighing the cylinders and measuring the volume with a helium picnometer (Table 2). The densities of the hot pressed samples were in good agreement with the densities used to calculate the relative volumetric proportions of glass

Table 1

	$\phi=0$	st.dev.	$\phi=0.5$	st.dev.	$\phi=0.7$	st.dev.	$\phi=0.5$; 10 h experiment	st.dev.
SiO_2	75.57	0.63	74.85	0.74	74.90	0.71	73.82	0.79
Al_2O_3	10.76	0.52	10.98	0.52	11.58	0.68	13.35	0.53
Na_2O	3.97	0.57	3.86	0.16	3.86	0.22	3.94	0.14
K_2O	4.39	0.35	3.78	0.19	3.75	0.17	4.00	0.09
Total	94.69		93.48		94.09		95.11	

Microprobe analyses of the matrix glass used in the experiments after hot isostatic pressing. Last two columns report analyses of the glassy matrix of a sample after 10 h of experiment. Abbreviations: ϕ = crystal fraction; st.dev. = standard deviation (2σ).

Table 2

ϕ (Crystal crystal fraction) nominal	0.5	0.7	0.9
Measured volume (cm^3)	5.154	4.733	4.075
	5.159	4.732	4.071
	5.157	4.730	4.069
	5.159	4.737	4.077
	5.159	4.732	4.078
Average (cm^3)	5.158	4.733	4.074
S.D.	0.002	0.003	0.004
Weight grams	16.025	16.622	15.667
Density	**3.107**	**3.512**	**3.846**
Calculated density	3.040	3.417	3.795
Geometrical volume	5.169	4.877	4.947
Open porosity %	0.228	2.950	17.648

Volumes were measured with a helium picnometer. The densities of the suspended particles and the glassy matrix were calculated with algorithms taken from the literature (see text for more details).

and particles (Table 2). The difference between the bulk volume measured with the caliper and the volume determined with the picnometer represents the interconnected porosity of the specimens. While the samples containing 0, 50 and 70 vol.% crystals had a porosity very close to zero, the synthesis of the sample with nominally 90 vol.% of crystals resulted in a residual porosity of 18 vol.% (Table 2). Based on
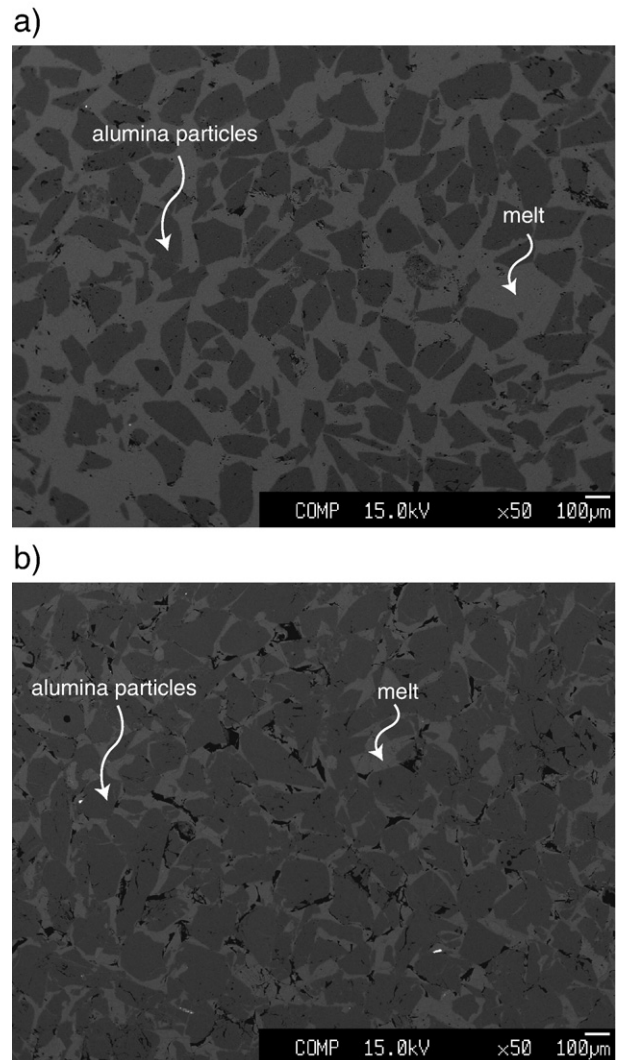

Fig. 1. (a) Back scattered electron image (BSE) of experimental sample with volume crystal fractions (ϕ) of a) 0.5; and b) 0.7.