Determination of the influence of pressure and dissolved water on the viscosity of highly viscous melts: Application of a new parallel-plate viscometer

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ABSTRACT

A parallel-plate viscometer has been designed for use in an internally heated pressure vessel (IHPV) at pressures up to 350 MPa and at temperatures up to 900 °C. The viscosity of a melt is determined by measuring the rate of deformation of a cylindrical sample as a function of an applied, constant stress at a fixed temperature. The viscometer consists of a small furnace with two independent heating resistors, a moveable load by which the stress is applied to the sample, and a pressure-resistant transducer (LVDT) that measures the deformation of the sample. The accessible viscosity range covers three orders of magnitude from $10^{8.5}$ Pa·s to $10^{11.5}$ Pa·s.

Calibration measurements on the standard melt DGG1 at 0.1MPa demonstrated the precision of the viscometer to be within ±0.08 log units. Subsequent measurements at elevated pressure on DGG1-melt, Di$_{100}$-melt (Di = CaMgSi$_2$O$_6$), and Ab$_5$Di$_{45}$-melt (Ab = NaAlSi$_3$O$_8$, composition in weight percent) showed a pronounced increase of viscosity with pressure. Comparison with literature data on the pressure dependence of the transformation temperature of Di$_{100}$-melt (Rosenhauer et al. 1979) confirmed the reliability of these findings. The dependence on pressure becomes smaller with increasing temperature for these depolymerized melts; e.g., in the case of Di$_{100}$-melt (NBO/T = 2) from $d\eta/dP = +0.23$ log units/100 MPa at 751 °C to $d\eta/dP = +0.18$ log units/100 MPa at 770 °C. In contrast to the depolymerized melts, a polymerized melt of haplotonalitic composition (NBO/T = 0) showed a decrease by −0.12 log units/100 MPa in the pressure range 50–350 MPa at 889 °C.

Possible application of the new viscometer to study rheological properties of volatile-bearing melts was tested successfully with a hydrous haplotonalitic melt. Addition of 3.80 wt% of water to the anhydrous melt strongly shifts the viscosity-temperature relationship toward lower temperatures; e.g., at a viscosity of $10^{10.5}$ Pa·s from 883 to 515 °C. The measured viscosities did not drift during the run, indicating that water loss is negligible within the time scale of the experiments, as confirmed by IR-microspectroscopic analysis.

INTRODUCTION

In recent decades, considerable effort has been made to determine the viscosities of volatile-bearing, and especially hydrous melts, over a wide temperature range at geologically relevant pressures (e.g., Shaw 1963; Kushiro 1978; Dingwell and Mysen 1985; Dingwell 1987; Persikov et al. 1990; White and Montana 1990; Baker and Vaillancourt 1995; Schulze et al. 1996; Scaillet et al. 1996). The first data for water-bearing melts were obtained using the falling sphere technique (Shaw 1963). This method allows only a small viscosity range to be investigated ($10^2$ to $10^5$ Pa·s), which is not always relevant to natural conditions (e.g., temperatures are too high for silica-rich melts). Furthermore, in the case of hydrous melts, the precision of the falling sphere technique is affected not only by serious experimental difficulties (Holtz et al. 1999) but also by poorly constrained melt densities at high P and T.

The extrapolation of viscosity data to lower temperatures has been hampered by the fact that up to now no generalized model existed to predict the temperature dependence of the viscosity of water-bearing melts. The widely used Arrhenius law (e.g., Shaw 1972; Persikov et al. 1990) fails to describe the temperature dependence of the viscosity of most silicate melts over a large temperature-range due to significant deviations from linearity (e.g., Richet and Bottinga 1995). Without measurements at lower temperatures and high pressure, the temperature dependence of viscosity due to the influence of pressure, as well as the influence of volatiles on the rheology of magmas, are poorly constrained.

One possibility for extending the viscosity range measurable by the falling sphere method was presented by Dorfmann et al. (1996) and Dorfmann et al. (1997). Using a centrifuge, viscosities up to $10^5$ Pa·s can be determined at a confining pressure of up to 100 MPa. However, the usefulness of this technique is probably limited, because for many melts of geological relevance, problems can arise due to crystallization on the time scale of the experiment.

Another approach to determine the viscosity of highly viscous, water-bearing melts involves measurements at ambient pressure using experimental techniques developed for anhydrous melts (micro-penetration, Dingwell et al. 1996, 1998;