

# Viscosity of hydrous kimberlite and basaltic melts at high pressures

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Received 20 April 2016; accepted 1 September 2016

## Abstract

New experimental data on the temperature and pressure dependences of the viscosity of synthetic hydrous kimberlite melts (82 wt.% silicate + 18 wt.% carbonate; degree of depolymerization:  $100 \cdot \text{NBO}/T = 313$  for anhydrous melts and  $100 \cdot \text{NBO}/T = 247$  for melts with 3 wt.% H<sub>2</sub>O) were obtained at a water pressure of 100 MPa and at lithostatic pressures of 5.5 and 7.5 GPa in the temperature range 1300–1950 °C. The temperature dependence of the viscosity of these melts follows the exponential Arrhenius–Frenkel–Eyring equation in the investigated range of temperatures and pressures. The activation energies of viscous flow for hydrous kimberlite melts were first shown to increase linearly with increasing pressure. Under isothermal conditions ( $T = 1800$  °C), the viscosity of hydrous kimberlite melts increases exponentially by about an order of magnitude as the pressure increases from 100 MPa to 7.5 GPa.

The new experimental data on the viscosity of hydrous kimberlite melts (error  $\pm 30$  rel.%) are compared with forecast viscosity data for anhydrous kimberlite and basaltic melts ( $100 \cdot \text{NBO}/T = 51.5$ ) and for hydrous basaltic melts ( $100 \cdot \text{NBO}/T = 80$ ). It is shown that at comparable temperatures, the viscosity of hydrous kimberlite melts at a moderate pressure (100 MPa) is about an order of magnitude lower than the viscosity of hydrous basaltic melts, whereas at a high pressure (7.5 GPa) it is more than twice higher.

It is first established that water dissolution in kimberlite melts does not affect seriously their viscosity (within the measurement error) at both moderate (100 MPa) and high (7.5 GPa) pressures, whereas the viscosity of basaltic melts considerably decreases with water dissolution at moderate pressures (100 MPa) and remains unchanged at high pressures ( $P > 3.5$  GPa).

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**Keywords:** viscosity; kimberlite; basalt; water; temperature; pressure; melt; model; mantle; Earth's crust

## Introduction

Magma viscosity largely controls important features of magmatic processes, such as, e.g., the movement of magmatic melts in the crust and the mantle, their origin, evolution, and stabilization in a variable field of temperature, pressure, and composition. Furthermore, the form of extrusive and intrusive rock masses, their textural characteristics, as well as the differentiation of magmas as a result of fluid–magma interaction, gravitational sedimentation, and partial melting are also limited by magma viscosity. The huge variety of major and volatile elements, the heterophase nature, and the wide range of temperatures and pressures are the main features of the existence of magmatic melts in nature. Experimental studies of the viscosity of such systems at high temperatures and

pressures are a complex technical and methodological problem (Persikov, 1991; Lange, 1994; and others). Despite significant advances in this area of petrology and geochemistry (Allwardt et al., 2007; Brearley et al., 1986; Chepurov et al., 2009; Dingwell et al., 2004; Fujii and Kushiro, 1977; Giordano et al., 2004; Kushiro, 1980; Lebedev and Khitarov, 1979; Lange, 1994; Liebske et al., 2003; Mysen et al., 1988; Neuville and Richet, 1991; Persikov, 1984, 1991, 1998, 2007; Persikov and Bukhtiyarov, 2004, 2009; Persikov et al., 1987, 1989, 1990, 2015; Reid et al., 2003; Scarfe, 1986; Scarfe et al., 1987; Shaw et al., 1968; Whittington et al., 2000; Wolf and McMillan, 1985), a number of problems remain unexplored, especially those concerning the viscosity of mafic and ultramafic melts at the  $TP$  parameters of their origin in the Earth's mantle. Experimental and theoretical data on the viscosity of kimberlite melts at the  $TP$  parameters of the crust and upper mantle were completely absent prior to our studies (Persikov et al., 2015a,b,c). Note that predicted data on the temperature and pressure dependences of the viscosity of synthetic kimberlite

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melts at pressures up to 7.5 GPa were first obtained in (Persikov et al., 2015), and the effective viscosity of heterogeneous (liquid + crystals + fluid phase bubbles) kimberlite magmas was first predicted in (Persikov et al., 2015) over a wide range of  $TP$  parameters corresponding to the conditions of origin of these magmas in the Earth's mantle and the conditions of hypabyssal facies, i.e., the formation of kimberlite dikes, sills, and diatremes. In recent experimental studies of the viscosity of natural kimberlite melts, Chepurov and Pokhilenko (2015) estimated the influence of the crystalline phase (up to 30 wt.%) on the effective viscosity of a heterogeneous kimberlite melt at a pressure of 4 GPa and temperatures of 1400 and 1600 °C.

In the present work, the effect of water dissolved in melts, temperature, and pressure on the viscosity of synthetic kimberlite melts was studied in a wide temperature range of 1300–1950 °C and at pressures of 100 MPa–7.5GPa. New experimental data on the viscosity of hydrous kimberlite melts ( $100 \cdot \text{NBO}/T = 247$ ) were compared with the calculated dependences for such melts, and the calculated dependences of the viscosity of anhydrous kimberlite melts ( $100 \cdot \text{NBO}/T = 313$ ), and the calculated dependences of the viscosity of anhydrous ( $100 \cdot \text{NBO}/T = 51.5$ ) and hydrous basaltic melts ( $100 \cdot \text{NBO}/T = 80$ ) which were obtained using a physico-chemical model for predicting the viscosity of magmatic melts (Persikov, 1998, 2007; Persikov and Bukhtiyarov, 2009; Persikov et al., 2015)

## Experimental and analytical methods

Selecting a representative composition of kimberlite magmas is not a simple problem. Despite the significant advances made in the petrology and geochemistry of kimberlite magmatism (Sparks et al., 2006, 2009; Wyllie, 1980), the problem of determining the composition of the melt from which kimberlites crystallize in the hypabyssal facies and especially the primary composition of the kimberlite magmas formed in the mantle, remains controversial (Kamenetsky and Yaxley, 2015; Kamenetsky et al., 2009; Sharygin et al., 2013; Sokol et al., 2013; Sparks et al., 2006, 2009; Wyllie, 1980). For example, it is assumed that the nucleation of kimberlite melts occurs through the reaction of carbonatite melts with peridotite near the mantle solidus and subsequent partial melting of carbonated peridotite at very low degrees of melting ( $\leq 1.0\%$ ) at pressures (6–10 GPa), depths of  $\approx 150$ –300 km, and a temperature  $\leq 1500$  °C (Dalton and Presnall, 1998; Dasgupta and Hirschmann, 2006; Kamenetsky and Yaxley, 2015; Kamenetsky et al., 2009; Karanagh and Sparks, 2009; Kopylova et al., 2007; Michell, 2008; Price et al., 2000; Sharygin et al., 2013; Sparks et al., 2006, 2009; Wyllie, 1980). Basaltic magmas can be generated in the asthenosphere through partial melting of garnet peridotite ( $\leq 25$  vol.%) at pressures of  $\sim 5.5$  GPa, depths of  $\sim 100$  km, temperatures of  $\sim 1350$  °C, and a water concentration in them  $\leq 1.0$  wt.% (Yoder, 1976; and others). Therefore, in the Table 1, the composition of the synthetic kimberlite melt used in our experiments is compared

with the average composition of unaltered hypabyssal kimberlite of the Udachnaya-East kimberlite pipe (Siberian Platform, Yakutia) selected as the representative composition of kimberlite magmas. The criterion for the comparison is not the concentration of the main rock-forming melt components, but the overall basicity of such melts, which has a decisive influence on their viscosity and is numerically determined using the structural-chemical parameter: the degree of depolymerization or the basicity coefficient  $K = 100 \cdot \text{NBO}/T$ . This structural-chemical parameter of melts adequately reflects the features of the overall chemical composition and structure of silicate and magmatic melts (Kopylova et al., 2007; Mysen, 1988; Persikov, 1984, 1991; Persikov et al., 1990, 2015). Obviously, the concentrations of rock-forming components in the synthetic kimberlite used in the present study are not strictly similar to those in natural kimberlites. However, the validity of the approach used to study the viscosity of magmatic melts has previously been tested in sufficient detail (Persikov, 1984, 1991; Persikov et al., 1990, 2015). Furthermore, this has made it possible for the first time to obtain ultramafic glasses with a high content (18 wt.%) of the molten carbonate phase which are stable (without degassing) both at moderate (100 MPa) and ultrahigh (7.5 GPa) pressures. The average basalt composition obtained in (Le Maitre, 1976) based on a statistical analysis of more than 3500 basalt samples from almost all regions of the world (Table 1) was selected as a representative composition of basaltic melts.

The starting materials for viscosity measurements of kimberlite melts were stoichiometric mixtures of natural minerals: albite (Ab,  $\text{NaAlSi}_3\text{O}_8$ ) from the Kolba massif (Kazakhstan) (Persikov et al., 1990) and calcite (Cal,  $\text{CaCO}_3$ ) from the Yoko-Dovyren layered intrusion (North-Baikal region, Russia) (Persikov et al., 2010b). It has been found in previous experiments that in contrast to hydrous silicate systems, in carbonate-silicate systems at increasing temperature and at moderate pressures (up to  $\sim 3.0$  GPa), solid-state reactions between carbonates and silicates with a release of a large amount of  $\text{CO}_2$  occur well before the melting of silicate and carbonate phases. As a result, the melts that formed differ from the starting mixtures in basicity and the content of  $\text{CO}_2$  and the carbonate phase; the concentration of the latter in the melt can vary widely, depending on the initial composition of the mixture (Fig. 1) (Persikov et al., 2012). The required synthetic kimberlite melt (82 wt.% silicate + 18 wt.% carbonate, Table 1) was synthesized by melting the starting mixture of powders of albite and calcite ( $\text{Ab}_{38}\text{Cal}_{62}$ , wt.%) in platinum capsules 6 mm in diameter and 60 mm high open at one end at  $T = 1300$  °C and at a  $\text{CO}_2$  pressure of 100 MPa, with a mass balance control in each experiment. The experiments were carried out using a high-pressure gas vessel with internal heating, equipped with a unique internal device which was described previously (Persikov and Bukhtiyarov, 2004; Persikov et al., 2010a,b) and which allows experiments at a fluid ( $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ) pressure to be carried out without changing the original geometry of the capsule with the melt. The time of the experiments was 4 h at  $T = 1300$  °C with a 1-h pre-exposure of the samples at  $T = 850$  °C to complete the

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