

# The Effects of the Concentration of Olivine Xenocrysts on the Viscosity of Kimberlite Melts: Experimental Evidence

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**Abstract**—The study of viscosity in sub-liquidus heterogeneous media, which includes kimberlite magma at the pressures and temperatures that prevail in the mantle, is an urgent task. We have conducted experiments in the serpentine–olivine, serpentine–CaCO<sub>3</sub>–olivine, and native kimberlite–olivine systems at a pressure of 4 GPa and temperatures of 1400–1600°C in a BARS high-pressure device using the technique of a falling Pt pellet. The samples were examined after experiments to find fine-grained chilled mass of crystals where the Pt pellet was observed at the time of chilling. The concentration of the solid phase was varied in the experiments between 10 and 50 wt %. We showed that when 50 wt % of olivine grains has been introduced, it was not possible to detect the motion of the Pt pellet, while when the concentration of olivine xenocrysts reached 10 wt %, the Pt pellet very rapidly descended to the bottom of the reaction volume. Viscosity was calculated using the Stokes method. We found that the viscosity of a homogeneous kimberlite melt at 4 GPa and 1600°C is below 2 Pa s, with the viscosity of a melt that contained up to 10 wt % of the solid phase being approximately constant. A kimberlite melt that contained 30 wt % of the solid phase had a viscosity on the order of 100 Pa s, while with 50 wt % of the solid phase the relative viscosity of an ultrabasic system increased to reach values over 1000 Pa s.

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## INTRODUCTION

The study of viscosity in kimberlite melts at the pressures and temperatures that prevail in the Earth's mantle is an urgent task. This is needed both for the development of geodynamic models to explain the movement of material in the crust and mantle and for improvements on methods of diamond prospecting. The experimental study of the rheologic properties for sub-liquidus heterogeneous (liquid + solid phase + gas) media, of which kimberlite magma is one, is of special value. Considering that there are substantial differences in theoretical estimates of viscosity for heterogeneous media, which is due to their complexity, it is extremely important to refine experimental techniques for determining the viscosity of a kimberlite melt that contains mineral crystals.

The main physical and chemical factors that give rise to discrepancies in relative viscosity derived by theoretical and experimental simulation of heterogeneous media are well known (Shaw, 1963; Pinkerton and Stevenson, 1992; Lejeune and Richet, 1995; Saar and Manga, 2002; Bouhifd et al., 2004; Caricchi et al., 2007; Giordano et al., 2008b; Castruccio et al., 2010; Hobiger et al., 2011). The factors include the abundance of solid particles in a melt (for example, the relative viscosity of melts with approximately 40 vol % of

crystals sharply increases (Bouhifd et al., 2004)), their shapes, orientation, and the distribution in the melt volume, and the variance of particle size. In addition, solid particles can move in the melt (either settling down or floating up) over time (Chepurov et al., 2011). The adhesion of minerals plays a large role, e.g., the wetting angle. The solid particles that are usually found in naturally occurring magmas are faceted crystals, growths, clasts of minerals and rocks. Kimberlite often contains such olivine crystals (Ol), which are usually elongate with length/width ratios ranging between 2 : 1 and 3 : 1 (Dawson and Hawthorne, 1969; Gernon et al., 2009).

As well, we still have insufficient knowledge of how chemical factors affect the viscosity of kimberlite melts. These factors include the degree of melt polymerization in relation to the concentration of SiO<sub>2</sub>, the effects of volatiles (H<sub>2</sub>O and CO<sub>2</sub>), and redox conditions (Liebske et al., 2003; Bouhifd et al., 2004; Hobiger et al., 2011). The common opinion is that the concentration of SiO<sub>2</sub> controls the viscosity of silicate melts, because it affects the degree of melt polymerization (Dingwell and Mysen, 1985; Romano et al., 2001; Giordano et al., 2004; Lacks et al., 2007). For andesitic and basaltic compositions, H<sub>2</sub>O is known to diminish melt viscosity (Giordano et al., 2008a;

Richet et al., 1996; Ardia et al., 2008). Kimberlite magma is characterized by low abundances of SiO<sub>2</sub> and high H<sub>2</sub>O and CO<sub>2</sub>, while the combined effect of these compositional features is unknown. In addition, a fluid phase can make the melt inhomogeneous and produce bubbles (Lejeune et al., 1999).

Temperature is an important factor that influences the estimates of the relative viscosity of kimberlite melts (Hess and Dingwell, 1996; Vetere et al., 2006; Giordano et al., 2008b), as is pressure (Kushiro et al., 1976; Persikov, 1991; Poe et al., 2006); all the more so, because kimberlite magmas were migrating from the Earth's interior toward the ground surface under varying *P–T* parameters. With respect to the *P–T* parameters during the origination and evolution of naturally occurring kimberlite magmas, we may note the following points. A study of mantle xenoliths showed that the temperature at the base of the continental lithosphere is estimated to lie in the 1350–1450°C range (Priestley et al., 2006). An adiabatic ascent of a type 1 kimberlite melt that contains 30% xenoliths reduces the melt temperature by 250°C (Kavanagh and Sparks, 2009).

The above discussion shows the complexity of determining the viscosity of a volatile-rich heterogeneous kimberlite magma under high *P–T* parameters. Theoretical simulation may give rise to substantial uncertainties because the many factors that affect the viscosity of such a system act in different directions. For this reason the present study was concerned with experimental estimation for the viscosity of several theoretical compositions and a real kimberlite melt under high *P–T* parameters.

## THE EXPERIMENTAL TECHNIQUE

The experiments were conducted on a multiple “dissected sphere” anvil apparatus (BARS, as abbreviated in Russian) using the method of a falling Pt pellet (Chepurov et al., 2009). The BARS apparatus consists of a spherical multi-punch unit placed in a case that can be opened very quickly; the case has a spherical inner cavity and in turn consists of an upper and a lower semi-case that are fastened to one another by a flange lock. The semi-cases contain self-operated chambers of high hydrostatic pressure (CHHP) that are made of the inner surfaces of the semi-cases and of the hemispheres of the sealing jacket. The semi-cases contain channels that act as oil feeders into the CHHP cavities. Each semi-case has three measuring electric leads and a power lead. The measuring leads are connected to electric contacts, which are situated on the sealing jacket and are pressed to the punch surface under the pressure exerted by the CHHP. The lower and upper semi-cases have a system of channels and nipples for cooling the multi-punch unit.

The type 8–6 multi-punch unit consists of two stages: an outer stage which includes eight punches

with a triangular operating platform and the inner stage which includes six octahedral punches. The inner operating cavity of cubical shape has a solid-phase high-pressure cell (HPC) that is placed inside along with a specimen.

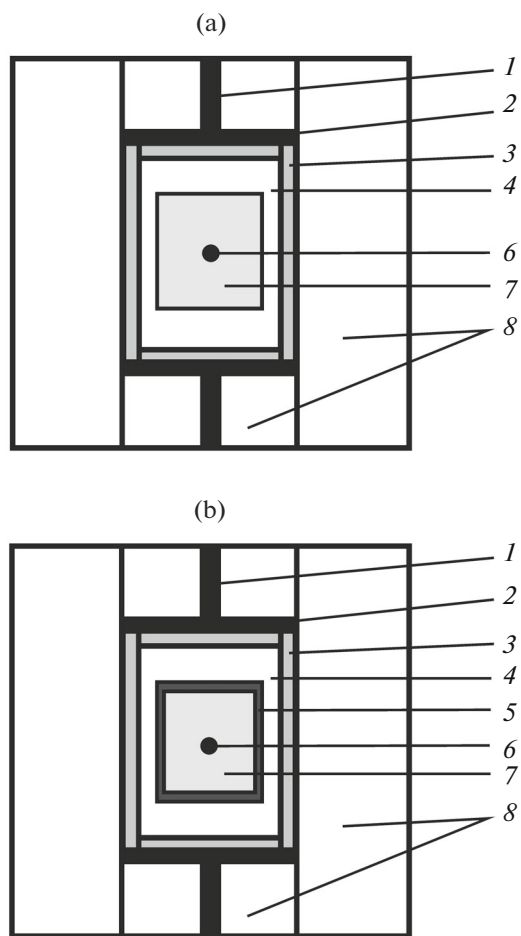
The pressure in the BARS HPC is generated as the punches converge toward the geometric center of the apparatus. Increasing external load is accompanied by increasing quasi-hydrostatic pressure in the HPC. The procedure for using the apparatus was described in (Chepurov et al., 1998, 2009, 2012).

The HPC was made by pressing refractory oxides (ZrO<sub>2</sub>, CaO, and MgO) together to obtain a rectangular 20 × 20 × 23-mm parallelepiped. A cylindrical graphite heater with lids was installed into a hole 11 mm in diameter at the center of the HPC (Fig. 1). The wall of the graphite heater was 0.5 mm thick, the electric leads were molybdenum rods and disks. The specimen was isolated from the heater by a sleeve with a 1-mm-thick wall, while the isolation from above and below was ensured by 2-mm-high washers made of pressed MgO.

Temperature was measured using a platinum thermocouple (Pt/Rh/30/6) installed in the HPC; the thermocouple was moved nearer the specimen through the lower lead cover. It was found during preliminary testing using two thermocouples that the temperature gradient at a temperature of 1500°C did not exceed 15°C/mm in the central zone inside the heater. The temperature in specimens placed at the center of the HPC was measured to within ±25°C.

Pressure was recorded by a manometer using a calibrated relationship between pressure in the HPC and the pressure of the oil in the CHHP. We used PbSe and Bi as reference elements for pressure calibration because they vary their electric resistance in relation to pressure. The well-known position of the graphite–diamond equilibrium line in the *P–T* coordinates (Kennedy and Kennedy, 1976) was used to introduce corrections for a change (increase) in pressure during subsequent heating. The rate of increasing pressure was fixed in the 0.1–0.2 GPa/min range. The pressure in the HPC was measured to within ±0.2 GPa.

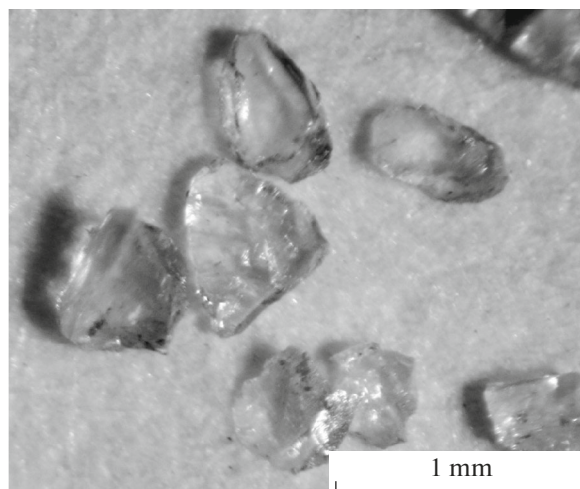
The specimens for this investigation were experimental charges that were pressed from the powder of original substances in the shape of a cylinder with a Pt pellet at the center. It is known that kimberlites from different pipes show considerable differences in chemical composition, while their chief components are an “olivine” and a “carbonate” component in the presence of a fluid phase (Dawson, 1980). The presence of the fluid phase, as well as of xenoliths of mantle and crustal rocks in kimberlites, give rise to uncertainty about the composition of the “type” of kimberlite melt. For this reason the specimens were chosen as several compositions that simulated naturally occurring kimberlites. We used the following model media: serpentine (Serp) + olivine (Ol); Serp + CaCO<sub>3</sub> + Ol; as well, we used naturally occurring kimberlite + Ol.



**Fig. 1.** Diagrammatic representations of the HPC without Pt ampoule (a) and with Pt ampoule (b). (1) Mo rod; (2) Mo disk; (3) graphite heater; (4) sleeve and disks made of MgO; (5) Pt ampoule; (6) Pt pellet; (7) specimen; (8) container made of a mixture of  $ZrO_2$ , CaO, and MgO.

The choice of Serp was based on the fact that it becomes a mixture of Ol and orthopyroxene above  $700^\circ\text{C}$  and releases  $H_2O$  (~13 wt %) into interstitions and into inclusions in newly formed minerals (Chepurov et al., 2010, 2012). The addition of  $CaCO_3$  makes the composition more similar to the naturally occurring kimberlite system.

The specimens were prepared for investigation as follows. Natural Serp (from Eastern Sayany ophiolites) and kimberlite (the Nyurbinskaya Pipe, Yakutia) (Table 1) were crushed and ground in a ball mill to obtain a powder with grains less than  $5\ \mu\text{m}$  across. The powder of  $CaCO_3$  (of the CP grade) was added to a powder of Serp at a weight ratio of 1 : 1 and carefully mixed in a mortar made of the VK-6 hard alloy. Natural Ol (see Table 1) from mantle xenoliths sampled on Shavaryn-Tsaram Volcano, Mongolia was crushed and sorted into fractions using sieves: less than 0.25 mm, 0.25–0.5 mm, and 0.5–1.0 mm with length to width ratios between 1 : 1 and 3 : 1 (Fig. 2). The choice of Ol



**Fig. 2.** Grains of original olivine.

was motivated by the fact that it is the most stable mineral in kimberlite compared with clinopyroxene, orthopyroxene, and garnet (Chepurov et al., 2013). Grains of Ol were added to prepared powders and mixed. One-half of the resulting mixture was poured into a pre-cut cylindrical press form and then pressed, a Pt pellet was put at the center of the upper butt-end of the resulting mould, the remaining half of the powder was poured from above and again pressed. The result was a cylindrical specimen with a Pt pellet at its center. When placed in a MgO capsule, the specimen was 8 mm in diameter and 7 mm in height. Pt pellets were made by melting pieces of Pt at a high pressure in a molten CsCl. We selected pellets 0.1–1.0 mm in diameter, with their dimensions being controlled using an MBI-15 microscope to within  $\pm 0.01\ \text{mm}$ .

Before the experiment, the mounted HPC together with the specimen inside were dried during 10 h at  $120^\circ\text{C}$  in a desiccator. The HPC was then placed in the apparatus and the apparatus was closed and sealed. The next step was to create pressure in the CHHP by pumping oil using an NGR-2000 pump. The water cooling of the internal power units was switched on. The specimen in the CHHP was heated by letting an electric current run from the power transformer through the graphite heater. The heating regime was set by an RIF-101 temperature regulator. The temperature was increased at a rate of  $700^\circ\text{C}/\text{min}$  until a preset value was attained. When the preset  $P$ – $T$  parameters were reached a time interval was allowed to pass (when the desired temperature was reached, the time was recorded using a digital stopwatch between the time the desired temperature was reached and the time of temperature drop, which is set by the operator) (Fig. 3).

The experiment parameters were 4 GPa and  $1400$ – $1600^\circ\text{C}$ . After the necessary time interval, the specimen was chilled while still under high pressure by

**Table 1.** The compositions of the original components

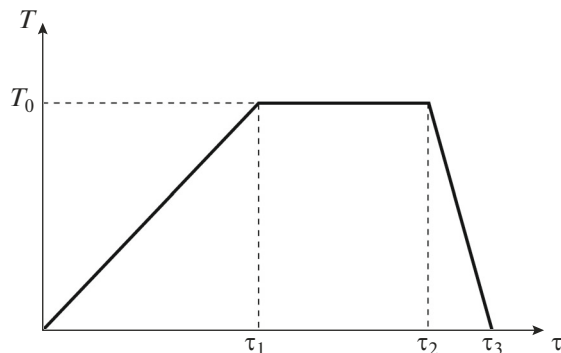
Component	Serp	Serp + CaCO <sub>3</sub> *	Kimberlite	OI
SiO <sub>2</sub>	41.53	20.74	32.08	40.7
TiO <sub>2</sub>	0.02	0.01	0.47	0.007
Al <sub>2</sub> O <sub>3</sub>	0.95	0.48	3.71	0
Cr <sub>2</sub> O <sub>3</sub>	0	0	—	0.037
FeO + Fe <sub>2</sub> O <sub>3</sub>	2.47	1.23	6.91	9
MnO	0.14	0.07	0.14	0.142
MgO	42.15	21.05	31.05	49.62
CaO	0.05	28.01	7.63	0.04
Na <sub>2</sub> O	0.47	0.24	0.47	0
NiO	0	0	—	0.41
K <sub>2</sub> O	0.02	0.01	1.74	0
P <sub>2</sub> O <sub>5</sub>	0	0	0.31	0
H <sub>2</sub> O**	12.42	6.20	16.18	0
CO <sub>2</sub>	—	21.96	—	—
Total	100.22	100	100.68	99.96

\* A mixture of powders of natural Serp and CaCO<sub>3</sub> in the weight ratio 1 : 1.

\*\* Loss on ignition.

switching the current off. The chilling time was 2–3 s, which was due to effective water cooling of the internal punch stage in the apparatus. The pressure drop was effected at a rate of 0.3–0.5 GPa/min.

After the experiment the specimen was sawed along the vertical axis and polished. The position of the Pt pellet was recorded using an MBS-10 microscope. The three recorded positions were as follows: (1) at the center, (2) between the center and the lower butt-end of the specimen, and (3) at lower end of the specimen (Fig. 4).



**Fig. 3.** The mode of heating.  $T$  is temperature,  $\tau$  is time,  $\tau_1$  is the time when a preset temperature was reached,  $\tau_2$  is the time when the time interval terminated,  $\tau_3$  is the time of experiment end,  $\tau_2 - \tau_1$  is the time interval for the specimen at set values of  $P$ – $T$ ,  $\tau_3 - \tau_2$  is the time of chilling for the specimen.

One of the more important measurable characteristics in these experiments for determining viscosity is the time the Pt pellet takes to fall in the melt, measured from the time the desired  $P$ – $T$  parameters were reached until the switching-off of current. The time of fall for the pellet is not sufficiently accurate in low-viscosity silicate melts (Chepurov et al., 2009), which is largely due to the temperature gradient in the cell, because melting begins at the center of a specimen and then propagates toward the butt-ends. Since the time the Pt pellet begins to move is not amenable to direct observation, we carried out a series of experiments to determine the time the pellet begins to move in the specimen, which was  $30 \pm 5$  s from the time the desired temperature was reached. When we calculated the time of motion of the Pt pellet, we subtracted the above value from the total time interval between the time the desired  $P$ – $T$  parameters were reached and the time of chilling. The time of chilling was set at  $2.5 \pm 0.5$  s. This difficulty of determining the velocity of the fall of a Pt pellet in a heterogeneous medium was probably also caused by the dynamics of the process, due to the fact that the pellet was not moving at a uniform velocity, which was not incorporated in the experiments.

## EXPERIMENTAL RESULTS

The experimental results are shown in Table 2. We wish to point out that no glass is produced during chilling of low silica melts; however, the melt rapidly crystallizes into a fine-grained mass of crystals where

a Pt pellet is formed at the time of chilling. The chilling matrix for the kimberlite composition consists of a mixture of the following mineral phases: olivine, phlogopite, clinopyroxene, and carbonate.

Viscosity was found by the Stokes method using the following well-known relation (Liebske et al., 2005):

$$\eta = [2r^2g(\rho_2 - \rho_1)/9V(1 + 3.3r/h)]K;$$

where  $\eta$  is the melt viscosity;  $g = 980 \text{ cm/s}^2$  is the gravitational constant;  $r$  is the pellet radius;  $h$  is the distance that the pellet traveled during the experiment;  $\rho_2 - \rho_1$  is the density difference between the pellet and melt;  $V$  is the velocity of the pellet falling in the melt;  $K$  is the correction for the wall effect in the ampoule found from

$K = [1 - 2.104(r/r_a) + 2.09(r/r_a)^3 - 0.95(r/r_a)^5]$ ; and  $r_a$  is the radius of the ampoule with the specimen inside.

The density of model melts was assumed to be  $2.8 \text{ g/cm}^3$ , which is the density of a peridotite melt with 5 wt %  $\text{H}_2\text{O}$  at  $P = 4 \text{ GPa}$  and  $T = 1700^\circ\text{C}$  (Sakamaki et al., 2009). The platinum density is  $21.45 \text{ g/cm}^3$  (Ardia et al., 2008).

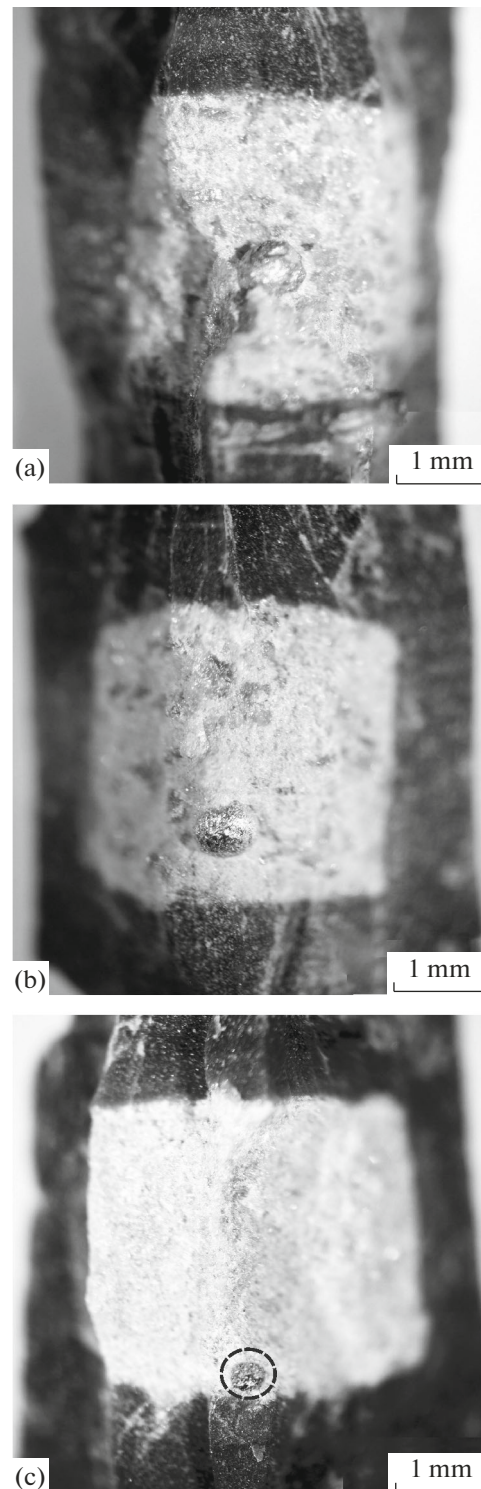
With 50 wt % or more of Ol grains introduced, we were not able to detect the motion of the Pt pellet with experimental parameters within 1 h. This shows that melts with the concentration of the solid component as indicated above have high viscosities. We estimate the viscosity of the system as being above  $1.2 \times 10^3 \text{ Pa s}$  (see Table 2). On the other hand, the Pt pellet was moving very rapidly when the concentrations of Ol grains were 10 wt % or less. The pellet took less than 10 seconds to reach the ampoule bottom.

With concentrations of 20 and 30 wt % of Ol grains we were able to obtain more correct viscosity values for the systems under study (see Table 2). It was found, as expected, that the velocity of the Pt pellets decreased; thus, the relative viscosity of heterogeneous media increased, unlike the case of melts with no solid phases.

It is thought (Pinkerton and Stevenson, 1992) that magmas with low concentrations of crystals can be treated as Newtonian fluids. In that case their relative viscosity can be estimated from the Einstein–Roscoe equation (Roscoe, 1952):

$$\eta = \eta_0(1 - \varphi/\varphi_m)^{-n},$$

where  $\eta_0$  denotes the viscosity of a homogeneous melt,  $\varphi$  is the concentration of crystals,  $\varphi_m$  is the maximum concentration of crystals, and  $n$  is an empirical constant. The quantity  $\varphi_m$  also depends on the dimensions, shapes, and distribution of the crystals, while  $n$  is controlled by the interaction forces that act on the crystals (Lejeune and Richet, 1995). Nevertheless, the Einstein–Roscoe equation is a popular tool for investigating the rheologic properties of naturally occurring multiphase lavas and magmas under sub-liquidus con-



**Fig. 4.** The position of the Pt pellet in the specimen after the experiments. (a) at center of specimen in original position (experiment no. 4-23-10); (b) in the body of the specimen (experiment no. 4-75-10); (c) at lower end (experiment no. 4-19-10) the pellet is open in part, the dashes outline the true dimensions.



**Table 2.** The results of experiments for determining relative viscosity ( $\eta_r$ ) for melts with olivine grains at a pressure of 4 GPa

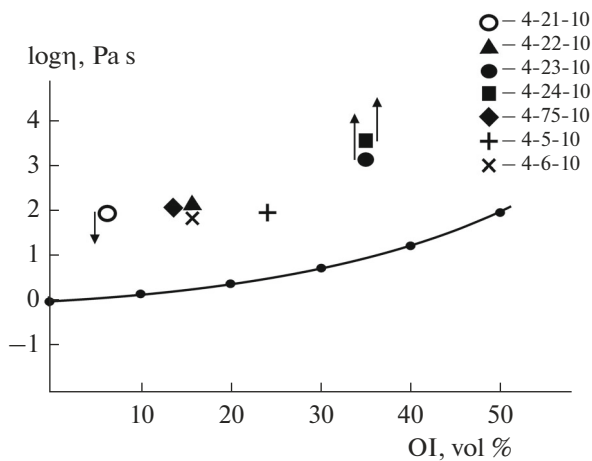
Experiment #	Concentration of Ol, wt %/vol %	$r$ , cm	$r_a$ , cm	$h$ , cm	$\tau$ , s	$l$ , cm	$V$ , cm/s	$K$	$\eta_r$ , Pa s
Serpentine at 1500°C									
4-19-10	—	0.012	0.3	0.4	40	0.19	$>1.9 \times 10^{-2}$	0.92	$<2.6$
4-21-10	10/~7	0.05	0.3	0.4	60	0.16	$>5.3 \times 10^{-3}$	0.65	$<8.9 \times 10^1$
4-22-10	30/~16	0.05	0.3	0.4	60	0.10	$3.3 \times 10^{-3}$	0.66	$1.4 \times 10^2$
4-23-10	50/~35	0.04	0.3	0.4	60	—	$<3.3 \times 10^{-4}$	0.79	$>1.2 \times 10^3$
4-24-10	50/~35	0.075	0.3	0.4	600	—	$<1.7 \times 10^{-5}$	0.71	$>3.1 \times 10^3$
A mixture of serpentine and calcite (1 : 1) at 1500°C									
4-75-10	20/~13.5	0.04	0.3	0.4	60	0.09	$3 \times 10^{-3}$	0.73	$1.2 \times 10^2$
Kimberlite at 1600°C									
4-3-11	—	0.015	0.3	0.4	35	0.19	$>3.8 \times 10^{-2}$	0.90	$<2.0$
4-5-11	30/~24	0.05	0.27	0.4	60	0.14	$4.7 \times 10^{-3}$	0.62	$9.5 \times 10^1$
Kimberlite at 1400°C									
4-6-11	20/~16	0.04	0.27	0.4	60	0.16	$>5.3 \times 10^{-3}$	0.70	$6.5 \times 10^1$

$r$  is the radius of the Pt pellet;  $r_a$  is the ampoule radius;  $h$  is the ampoule height;  $\tau$  is the waiting time;  $l$  is the length of the pellet movement;  $V$  is pellet velocity;  $K$  is a correction for the wall effect in the ampoule.

ditions (Petford and 2009). The usual assumption for calculation is that  $\phi_m$  and  $n$  are set to 0.6 and 2.5, respectively (Marsh, 1981; Lejeune and Richet, 1995). The equation thus becomes

$$\eta = \eta_0(1 - \phi/0.6)^{-2.5}.$$

The viscosity values derived from the Einstein–Roscoe equation differ considerably from the Stokes results (Fig. 5). Direct measurements via the method of a falling Pt pellet showed that these differences can



**Fig. 5.** The relative viscosity of heterogeneous melts as a function of the concentration of olivine grains (Ol). The light line was calculated from the Einstein–Roscoe equation (Roscoe, 1952). Different symbols denote experiment numbers.

reach 3 orders of magnitude for, e.g., a concentration of Ol equal to 30 wt % ( $\phi = 0.36$ ) in a kimberlite melt.

Considerable deviations between experimental and theoretical data have been obtained, e.g., by H. Sato (2005) for a basaltic melt under sub-liquidus conditions at atmospheric pressure. This author found the following increases in viscosity as the temperature was reduced: 52 Pa s at 1230°C, 350 Pa s at 1170°C, and 1950 Pa s at 1130°C. This resulted from increasing amounts of crystals in the melt during crystallization. The theoretical values obtained from the Einstein–Roscoe equation for spherical solid particles show a much smoother dependence. It was convincingly demonstrated that the discrepancies between measured and theoretical values of relative viscosity in a multiphase medium is due to the morphology of the solid particles.

The use of the Einstein–Roscoe equation for calculating the relative viscosity of multiphase silicate systems under sub-liquidus conditions is subject to considerable restriction (Ishibashi and Sato, 2007; Petford, 2009). In addition, our study had to deal with Ol xenocrysts of irregular shapes. These were in disequilibrium with the kimberlite melt; thus, some interaction was inevitable; this is not incorporated in the Einstein–Roscoe equation. A microscopic study of polished sections of products after the experiments showed that the surface of Ol grains is corroded by the melt to depths of 10–20  $\mu\text{m}$  in experiments with a total duration inside 3 min (the time interval when Ol grains were allowed to reside in the melt was 1 min or less).

## DISCUSSION

It is a common belief that kimberlite magmas are generated at depths of over 150–200 km. As the magmas are migrating toward the ground surface, their composition varies strongly due to mantle and crustal xenoliths that are captured. According to Moss et al. (2009), the study of the time-dependent behavior for eruptions of kimberlite magmas is complicated by the following factors. First, a kimberlite eruption has never been directly observed, while the craters of even the youngest kimberlite volcanoes are usually strongly eroded or completely removed. Secondly, primary samples of kimberlite melts are rarely preserved, because deposits of kimberlite volcanoes are highly sensitive to later alteration and structural modification. Thirdly, kimberlite magmas are rich in volatiles and probably experience strong changes in their physical properties as they are moving toward the ground surface and then erupting. Since kimberlite magmas involve high concentrations of volatiles, the volumetric melt/solid-phase/gas ratios may exhibit evolution from melt-dominated systems under mantle conditions as far as gas-dominated systems during eruptions (Price et al., 2000; Sparks et al., 2006; Gernon et al., 2009).

The reconstruction of the original composition of kimberlite melts remains a difficult problem. Nevertheless, there are several hypotheses about the composition of kimberlite magma. As an example, Sparks et al. (2009) listed the following compositions of the main components (wt %): SiO<sub>2</sub> between 25 and 35, MgO between 25 and 35, CaO between 12 and 20, and CO<sub>2</sub> between 5 and 12. Calcite of magmatic origin, which is present in kimberlites, points to a significant role of CO<sub>2</sub>, while phlogopite is a common mineral among phenocrysts and minerals in the groundmass. In addition, there is a direct argument in favor of the presence of H<sub>2</sub>O in kimberlite magmas, viz., an absence of orthopyroxene xenocrysts because orthopyroxene will react with a water-bearing magma (Mitchell, 2008). According to (Brey and Ryabchikov, 1994; Dreibus et al., 1995), the concentration of CO<sub>2</sub> in the primary kimberlite magma may exceed 20 wt %, although the mean concentration of CO<sub>2</sub> in kimberlites is ~5 wt %. Much of the carbonic acid may be lost during the ascent (Girnis et al., 2005). Price et al. (2000) made a detailed study of aphanite kimberlites from the Jerico Pipe, Canada to infer from these data that the primitive melt contained approximately 17 wt % CO<sub>2</sub>. A similar estimate for the concentration of CO<sub>2</sub> (~17 wt %) in kimberlite melt was obtained by Patterson et al. (2009). It is thought that carbonate and carbonate–silicate melts, of which kimberlite magma is one, possess a great penetrating ability through the Earth's upper mantle (Hammouda and Laporte, 2000).

The issues under debate also include the concentrations of primitive and xenogenic Ol. As an example,

Mitchell (1986, 2008) hypothesized that kimberlite magma contains ~25 vol % of Ol xenocrysts and ~25 vol % of Ol phenocrysts. However, structural studies have shown that the concentration of Ol phenocrysts should be revised and is actually approximately 5 vol % (Brett et al., 2009). The results of a study (Sobolev et al., 2015) provide evidence that idiomorphic Ol crystals in kimberlites also have central zones of irregular shapes and that these zones are part of a high-baric genesis of pyrope lherzolites, that is to say, they seem to have been xenocrysts during the earlier phase in kimberlite generation.

Geological and petrologic observations and experimental studies have shown that kimberlite magma proper has an extremely low viscosity. This is supported by the following geological and petrologic observations. First, lapilli usually have very thin mineral films in the groundmass, which are interpreted as chilled melt, while the rounded shape of the lapilli is controlled by surface tension (Sparks et al., 2006). Secondly, the kimberlite found in hypabyssal intrusions forms dikes approximately 1 m thick and occasionally may make a set of veins that are only a few centimeters thick (Kopylova et al., 2007). Thirdly, endogenous inclusions do not contain amygdules or bubbles, which are common in magmas that are very rich in gases (Dawson, 1981). This occurs because the low viscosity of kimberlite magma favors effective release of volatiles (Brown et al., 2008).

The viscosity of kimberlite magma must be close to that of peridotite melts. Experimental studies (Dingwell et al., 2004) have shown that peridotite melt has viscosities in the range between 0.7 Pa s at 1500°C and 1.5 Pa s at 1200°C. The Stokes method was applied to diopside melt at 4 GPa and 1800°C (Chepurov et al., 2009) to obtain a viscosity of 0.63 Pa s, which is fairly consistent with the data obtained using synchrotron radiation (0.31 Pa s at 3.5 GPa and 1730°C) (Reid et al., 2003). It is thought that considerable proportions of Ol crystals in a melt can increase the viscosity by factors of 10–100 (Pinkerton and Stevenson, 1992). Persikov and Bukhtiyarov (2014) used a physicochemical model of their own to obtain theoretical predictive viscosities for kimberlite magma during its ascent from mantle to the crust. As an example, the viscosity of kimberlite magma is 35 Pa s at 9 GPa and 1400°C and it decreases to reach 11 Pa s at 5 GPa and 1200°C, although the temperature is lower by 200°C.

Our data show that the viscosity of kimberlite melt is below 2 Pa s at 4 GPa and 1600°C, while it is below 2.6 Pa s in a system whose bulk composition is that of serpentine at 1500°C (see Table 2). Thus, the results are close to one another and are in agreement with the experimental findings described above. It is of interest that the viscosity remains very low when the concentration of Ol xenocrysts is below at least 10 wt %. The viscosity increases as the concentration of xenocrysts increases: by 1–2 orders of magnitude at 20–30 wt %

(for all systems studied) and by 3 orders of magnitude at 50 wt % (see Table 2).

This indicates that very rapid motion of a liquid is impossible through narrow fissures with this concentration of the solid phase, which is explainable by the decrease in transmissive capacity of the fissure due to the presence of crystals and increased internal friction during interaction between the melt and the crystals. Two variants emerge: (1) kimberlite magma must contain sufficiently low concentrations of the solid phase (below 30 wt %) and (2) in the other case, kimberlite material can be moved only during explosive processes. The relationship among solid phases, liquid, and gas can produce either effusive or explosive types of eruption (Moss et al., 2009).

The measurements of the relative viscosity for ultrabasic systems in our experiments are merely rough estimates, although the reproducibility of the results is reasonably high. This is due to several factors, as outlined above. However, even very approximate estimates are important for the study of processes in mantle and crust. The existence of naturally occurring homogeneous kimberlite magmas with no solid phase and volatiles is unlikely. As the concentration, dimensions, and shapes of the solid phases in a kimberlite melt are varied, the values of relative viscosity that are determined experimentally can jump from very low to very high values. It should also be added that our experiments did not incorporate the appearance of phenocrysts that crystallize in the kimberlite melt itself. For this reason we need to continue our studies on the influence of these factors as influences on the viscosity of heterogeneous kimberlite melts.

### CONCLUSIONS

Kimberlite melt that contains few solid-phase particles (Ol) has a very low relative viscosity at 4 GPa and 1600°C. The viscosity of kimberlite melts with the concentration of the solid phase below 10 wt % is not likely to be very different. Viscosity progressively increases with increasing concentration of the solid phase. A kimberlite melt that contains 30 wt % of the solid phase has a viscosity on the order of 100 Pa s. When the concentration reaches 50 wt %, the relative viscosity of ultrabasic systems increases to reach values over 1000 Pa s. Magmas with high concentrations of the solid phase (over 30 wt %) may be decelerated in their movement due to their high relative viscosity and may even plug conduits or else appear on the ground surface following the explosive type of eruption.

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