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鉄に富むかんらん岩メルトの粘性率測定

Viscosity measurements of iron-rich peridotitic melts

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1. Introduction

Viscosity is the most fundamental transport property to understand nature and dynamics of magmas in the Earth. Efforts have been made to understand viscosities of SiO_2-rich silicate melts such as basaltic and andesitic compositions at high temperatures under atmospheric pressure condition1), which are important to discuss dynamics of volcanoes in the current Earth. On the other hand, knowledge of the viscosity of SiO_2-poor peridotitic melt is fundamental to discuss nature and dynamics of the magma ocean in the early Earth. However, the viscosity of peridotitic melt has not been well investigated, due to experimental difficulties such as high melting temperature, high reactivity, and/or low viscosity.

Some studies have investigated viscosities of peridotitic melts using falling sphere viscometry under high pressure conditions2), 3). These studies provided important information on the viscosities of some peridotitic melts. However, there are three issues in the current knowledge of the viscosities of peridotitic melts: (1) Temperature condition of the falling sphere viscosity measurement is limited just above the melting temperature, because the probing sphere in the sample falls immediately after melting of the sample. Therefore, it is not possible to determine temperature dependence of the viscosity, which is critical to model the viscosity of magmas in the Earth. (2) Since melting temperature is different in different sample compositions, which make it difficult to compare viscosities of different sample compositions. (3) It is difficult to conduct falling sphere viscosity measurement in iron-rich silicate melt compositions, because of high reactivity of iron in silicate melt with the probing sphere made from metal.

In order to overcome these experimental difficulties, we utilize the electrostatic levitation furnace (ELF) at the Internation Space Station (ISS). The ELF is capable of conducting high temperature melt experiment at >3000 K by laser heating, which enabled us to melt SiO_2-poor peridotitic compositions and to investigate temperature dependence of the viscosity at wide range of temperature conditions. In addition, the ELF measures viscosity of molten sample under levitated environment, which avoids reaction of iron in silicate melt sample with container material. In this study, we investigated viscosities of three iron-rich peridotitic melts ($Mg_{1.8}Fe_{0.2}SiO_4$, $Mg_{0.7}Fe_{1.2}SiO_4$, $Mg_{0.9}Fe_{1.6}SiO_{4.5}$) at high temperature conditions between 1980 K and 2569 K by using the ELF at the ISS.

2. Viscosity measurement

Viscosity measurements were conducted by using the drop oscillation method in the ELF at the ISS[4]. Sinusoidal voltages excite an oscillatory deformation on the melt sample. When the excitation voltage is stopped, the sample oscillation gradually weakens due to its viscosity. Fig. 1 shows an example of the oscillation obtained in the $Mg_{1.8}Fe_{0.2}SiO_4$ melt sample at 2308 K. The obtained experimental oscillation data was fit into the following equation:

$$y = Ae^{-\frac{t}{\tau}}\sin(2\pi f_0 t + \phi) \ ,$$

where A, τ, f_0, and ϕ is amplitude, decay time, resonant frequency, and phase, respectively. Then, the viscosity η is calculated by:

$$\eta = \frac{\rho r^2}{5\tau} \ ,$$

where ρ and r is the density and radius of the sample.

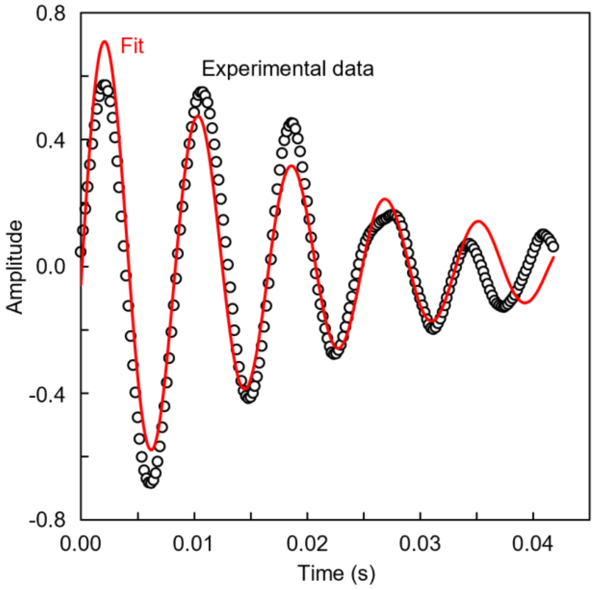

Figure 1. An example of the experimentally obtained oscillation data of the $Mg_{1.8}Fe_{0.2}SiO_4$ melt sample, and the fit result.

3. Results and discussion

We succeeded to determined viscosities of $Mg_{1.8}Fe_{0.2}SiO_4$ melt at 2197-2361 K, $Mg_{0.7}Fe_{1.2}SiO_4$ melt at 2094-2569 K, and $Mg_{0.9}Fe_{1.6}SiO_{4.5}$ at 1980-2283 K. The viscosity results at high temperature conditions are fit into an Arrhenius relation. Our obtained viscosity results of the SiO_2-poor and iron-rich peridotitic melts are compared with those calculated based on the viscosity model of Giordano et al. (2008)[1], which is determined based on the viscosity data of SiO_2-rich silicate melt compositions. Extrapolation of the Giordano's model to

SiO_2-poor peridotitic melts yielded similar viscosity values at ~2200-2300K, while we found marked difference in the temperature dependence of the viscosities. Our results show markedly lower temperature dependences of the viscosities of the $Mg_{1.8}Fe_{0.2}SiO_4$, $Mg_{0.7}Fe_{1.2}SiO_4$, and $Mg_{0.9}Fe_{1.6}SiO_{4.5}$ melts than those calculated by the Giordano's model. On the other hand, temperature dependence of the viscosity of Mg_2SiO_4 melt calculated by first principles simulation5) is similar to our results, while our determined viscosity value of the $Mg_{1.8}Fe_{0.2}SiO_4$ melt at 2300 K (32.2 mPa s) is 44 % higher than that of Mg_2SiO_4 melt at the same temperature (18.1 mPa s) calculated by Ghosh and Karki (2011)5).

In addition, our results show that viscosities of $Mg_{0.7}Fe_{1.2}SiO_4$ melt are higher than those of $Mg_{1.8}Fe_{0.2}SiO_4$ melt, which indicate increase of viscosity by increasing iron content. The result is in contrast to the Giordano's model, in which iron decreases the viscosity. In addition, a previous experimental study6) has investigated viscosities of $Mg_{1.95}Si_{1.05}O_{4.05}$ melt at 2293-2461 K and Fe_2SiO_4 melt at 1439-1685 K. Although it is difficult to directly compare these two results due to significantly different temperature conditions, the viscosity of the Fe_2SiO_4 melt seems lower than that of $Mg_{1.95}Si_{1.05}O_{4.05}$ melt, which is in contrast to our results. In addition, first principles simulation studies show that viscosity of Fe_2SiO_4 melt7) is lower than that of Mg_2SiO_4 melt5). One possible interpretation of the discrepancy is different effect of Fe^{2+} and Fe^{3+} on the viscosity of silicate melt. Although valence state of iron in the silicate melt sample has not been reported in the previous study, we measured valence state of iron in our recovered samples by X-ray absorption near edge structure (XANES) measurement at the BL27SU beamline in SPring-8. Our samples show the $Fe^{3+}/\Sigma Fe$ ratio of 0.22-0.23. The Fe^{3+} may polymerize the melt structure8), and the polymerization by the Fe^{3+} may be the origin of the increase of viscosity obtained in this study.

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